THE HYDROLOGY OF A RECENTLY DRAINED PEAT BOG IN SOUTHERN SCOTLAND

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ABSTRACT

This thesis reports on a study of the hydrology of a peat bog recently drained for forestry purposes in South East Scotland. The literature relating to the hydrological consequences of peat drainage is reviewed and the controversy surrounding this subject is outlined and discussed. A need for detailed experimental work, particularly on hydrological processes, is identified, and reasons are given for the selection of the particular site. The characteristics of the experimental area as well as the various experiments carried out are described in detail. Particular attention is given to the application and use of lysimeters and runoff plots for this type of field work.

The results obtained are presented in four sections relating respectively to: the water balance, runoff processes, the relationship between water table depth and flow rates, and conceptual modelling. These results show that the various aspects of the hydrology of the site are strongly influenced by the hydrological behaviour of the open ditches. As far as water balance results are concerned the study indicates that the open ditches, which make up 30 % of the total area, have evaporation losses amounting to only c. 40 % of the potential evapotranspiration. The strips between ditches, on the other hand, were rather unexpectedly found to have evapotranspiration losses close to the potential evapotranspiration. The very low values of evaporation from the ditches mean that evapotranspiration losses from the whole area are also lower than potential evapotranspiration. The runoff processes studies showed that, during storms, saturation overland flow originated by direct rainfall onto the ditches dominates the quick catchment responses and that during such periods the ditches behave, to all intents and purposes, as impermeable areas. Rain falling onto the strips between ditches seems to infiltrate freely to the main water table and most of this water moves slowly towards the ditches through the lower peat layers. When the water table is near the top of the peat profile a quick response of interflow emerges at the ditches from the upper peat layers. In spite of the few available data, a reasonable relationship was found between flow rates from the strips and water table depth. This work also shows that the temporal distribution of runoff can be reasonably simulated by a very simple conceptual model based on the main experimental findings.

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PART 1

INTRODUCTION

1.1 General Introduction

Drainage of peatlands for forestry is a current practice in several countries of the world. Such drainage is a way of lowering the water table and thus increasing the volume of aerobic soil available to tree roots (Malcolm, 1981). In this way forest productivity may be increased (Boggie and Miller, 1976; Seuna, 1974; Heikurainen, 1968) and stability of stands, in windy climates, may also be improved (Malcolm, 1981; Henman, 1963).

Peatland drainage for forestry is usually implemented by the construction of a network of parallel open ditches using ploughs. The spacing and depth of the ditches may vary according to the topography and type of peat of the area (Thompson, 1979). Various types of ploughs and drainage schemes currently used in Britain are described by Thompson (1978, 1979).

Land use changes such as the creation of a drainage scheme must in theory change the hydrologic behaviour of the areas concerned (McDonald, 1973). These changes may influence the hydrological response of entire catchments and thus eventually may affect those using, or interested in using, the water resources of the areas concerned. The study of this subject is becoming of more and more importance as the areas of peatland drained forestry increase with time. In the present work an attempt is made to derive an understanding of the hydrological behaviour of a recently drained peat area in South East Scotland.

The influence of drainage on the hydrology of peatlands has been a subject of concern in many parts of the world. Most of the work done in this field concerns areas drained for agricultural purposes. Important work in this area has been done in the Soviet Union, Germany and Ireland. Mole drainage and tile drainage constitute the most common types of drainage schemes used for agricultural purposes. The influence of forest drainage on the hydrology of peatlands has been studied mainly in Finland and some work has also been done in the Soviet Union and Great Britain. A literature review on the effects of drainage, either for agricultural and forestry purposes, on the hydrology of peatlands is given in the following paragraphs in order to frame the aims of the present work.

As the main objective of drainage is lowering the water table, the study of the influence of water table depth on evapotranspiration of natural vegetation of bogs, is of crucial importance to the understanding of short-term influences of peat drainage on the water balance. Several authors have studied this subject intensively. Virta (1966), working with lysimeters in Finland, showed that the lowering of the water table from ~2 cm below the surface to ~15 - 16 cm below the surface resulted in a substantial decrease in evapotranspiration. On the other hand Nichols and Brown (1980), in the United States, found no change on the evapotranspiration of samples of *Sphagnum* bog when the water level was lowered from 5 cm to 15 cm below the surface. Romanov (1968a, 1968b) in his study of bogs in the U.S.S.R. found little change in evapotranspiration when the water table was lowered to $\sim$30 cm below the surface. For lowerings bigger than this threshold, marked reductions on evapotranspiration were observed. Romanov (1968b) also stated that these results indicated that for water table depths bigger than $\sim$30 cm, the upper boundary of the capillary fringe dropped below the paludine dwarf shrubs which dominated the areas studied. These results agree with the work of Boelter (1964), in the United States, who found that capillary rise was not higher than 20 to 30 cm for undecomposed peat. Using bottomless tanks to measure evapotranspiration from a bog surface of Sphagnum moss and low-growing vascular plants, Boelter (1972a) found that with a water table depth of 30 cm evapotranspiration losses were less than half of those occurring when the water table was at the surface. This reduction on evapotranspiration was primarily due to the dessication of Sphagnum mosses.

Romanov (1968b) stated that, on a short-term basis, drainage of bogs considerably reduced evapotranspiration and thus increased runoff by factor of 1.3 - 1.5. This reduction in evapotranspiration due to drainage was explained by the fact that a decrease in water table level was accompanied by a reduction of the specific evapotranspiration (i.e. evapotranspiration per unit of absorbed energy) of the soil surface covered by natural vegetation. These findings were confirmed by Bulavko (1971) in a review of past work on the Byelorussian SSR. He stated that after drainage for agricultural purposes, water level drops by 1.0 - 1.5 metres, the natural vegetation is destroyed and as a result evapotranspiration decreases by 40 - 50 percent. With the progressive occupation of the drained land by agricultural crops, evapotranspiration increases again but still remains 10 - 15 percent below its original value. As a result of the extensive drainage on the Byelorussian region the annual flow of some rivers has increased by as much as 30 percent. This increase was particularly important during low flow periods (summer and winter). This general pattern of behaviour of the hydrology of drained areas is confirmed by several other authors (Bulavko and Drozd, 1975; Klueva, 1975; Zubets and Murashko, 1975).

The increase of annual flow immediately after drainage can also be partially explained by the release of some water that, in an undrained situation, would be stored in the upper layers of the peat (Burke, 1975b). This release of stored water produces, as a consequence, the subsidence of the peat and the lowering of the water table within the drained area. Moklyak et al (1975) and Kubyshkin (1975) discussed cases where the annual flow decreased rather than increased, in a long-term basis after drainage. They also suggested that this could be due to additional evapotranspiration from the drained land resulting from its intensive cultivation, or to groundwater losses by deep infiltration.

Drainage for agricultural purposes may also modify the temporal distribution of flow by modifying the relative importance of quick and delayed flow on flow generation processes. Burke (1968, 1975a, 1975b), Eggelsmann (1975) and Baden and Eggelsmann (1964) cited by Dooge (1975) produced evidence showing that after drainage for agricultural purposes the lowering of the water table can increase the temporary water storage capacity of the peat so that outflow from the area becomes much more uniform. Floods were found to be reduced in frequency and amount and low flow levels were increased in the short-term. Burke (1968, 1975a), Eggelsmann (1975) and Baden and Eggelsmann (1968) showed that flood hydrographs in drained areas begin later, have lower peaks and higher and more prolonged recession limbs than corresponding flood hydrographs from undrained areas. This situation can be explained by the dominance of surface runoff in undrained areas while in the drained areas water percolates through the soil to the tile drainage system (Eggelsmann, 1975; Baden and Eggelsmann, 1968). This regulating effect of drainage for agricultural purposes on peatland outflow is also confirmed, on a seasonal basis, by Bulavko and Drozd (1975), Zubets and Murashko (1975) and Klueva (1975). It is generally accepted by the previous authors that the increase in time and amount of low flows, due to agricultural drainage, is a significant improvement in the pattern of outflow from peatlands. This conclusion is of importance since it has been recently shown, in several parts of the world, that undrained peat, contrary to what was believed in the past, has very little water retention capacity and thus has little regulating effect on flows (Boelter and Verry, 1977; Eggelsmann, 1975; Bulavko, 1971; Bay, 1969). It has been observed, however, that a drainage scheme for agricultural purposes may increase stream density by 2 to 5 times, which is considered to increase surface run-off (Bulavko and Drozd, 1975).

As was stated at the beginning of this introduction drainage for forestry purposes is implemented by different techniques to those currently used for agricultural purposes. By ploughing the soil a dense network of open ditches is created and these ditches are usually the basis of a forest drainage scheme.

The influences of forest drainage on the hydrological behaviour of peatlands have been less studied than the influences of agricultural drainage schemes. However, some work has been done recently in this field. In Finland, Seuna (1974) and Mustonen and Seuna (1975) studied short-term influences of forest drainage by a controlled basin experiment. After draining 40 percent of the watershed under study, an increase of 43 percent in annual flow was observed mainly due to a decrease in evapotranspiration. The increase in the total outflow was relatively evenly distributed through the year. On the other hand Vompersky (1974), in U.S.S.R., comparing drained peatlands with well established forests (aged 25 - 30 and 70 - 90 years) with undrained areas, found that the total amount of flow from the afforested peatlands was much smaller than the total amount of flow from undrained peatlands. Commenting on the results of Seuna (1974) and Vompersky (1974), Kuntze (1974) emphasizes the necessity of a distinction between short-term and long-term influences of forest drainage. According to Kuntze (1974) immediately after drainage evapotranspiration will be reduced but it will recover, and even exceed, its original value due to the progressive increase in transpiration and interception by the growing trees, and thus the initially increased total flow will decrease again with time. As a conclusion to his comments he states that with time Seuna will get similar results to the ones reported by Vompersky. These considerations of Kuntze were later confirmed by Seuna (1980) who showed that the initially increased annual runoff from drained areas progressively decreases with time and after 15 - 20 years reaches again its pre-drainage value. Reviewing past work in this field, Heikurainen (1975) also draws general conclusions similar to those of Kuntze (1974).

The influence of a drainage network of open ditches on the temporal flow pattern has also been studied in some works. Conway and Millar (1960), in Britain, comparing outflow responses of recently drained blanket peat catchments with outflow responses of undrained blanket peat catchments, showed that the hydrographs were much more flashy in areas having a network of open ditches. Hydrographs from drained catchments showed quicker and higher flood peaks and the recession limbs were shorter and lower than in corresponding hydrographs from undrained areas. Howe et al (1966) emphasized that drainage for forestry increases the length of the stream network, which is considered to increase flood magnitude and flood frequency. A good relationship was found by them between drainage density and mean annual flood per unit area. Ahti (1980), in Finland, found that maximum peak flows were inversely proportional to ditch spacing. Seuna (1974) and Mustonen and Seuna (1975) have also shown that, in recently drained peatlands for forestry purposes, maximum spring and summer runoff increased 31 and 131 percent on average respectively. This was attributed to the accelerating effect of the drainage network. They also found a significant increase, after drainage, in winter and summer minimum flows.

The influence of a network of open ditches on the hydrologic response of drained areas for forestry is particularly emphasized by Binns (1979). He states that :

"Drains....have the obvious effect of removing water very rapidly and, because up to 20 per cent of the land may consist of ditches, 20 per cent of any storm will fall directly into these ditches and leave the site within a very short time. Thus the hydrograph on a recently drained catchment will show a more rapid response to rainfall than before drainage..... As the trees grow towards the thicket stage they evaporate more and more water but to begin with, this only compensates for the suppression of natural vegetation. Grass and other plants grow over the ridges and the furrows of cultivation and over the ridges from drains, which starts to return to a less flashy hydrograph."

On the other hand Heikurainen (1975) considers that:

"Variations in the temporal distribution of the runoff as a function of the time that has been elapsed since draining cannot be predicted without more detailed investigation. However, the greater water storage capacity of peatlands after draining and the delayed snowmelt as the tree stand develops, probably produce lower flood peaks of longer duration. The influence of the ditches themselves is, however, probably the reverse".

In a later paper, Heikurainen <u>et al</u> (1978) emphasize the necessity to distinguish between short-term and long-term hydrological influences of forest drainage. According to them, the immediate influence of forest drainage can be seen in a very strong rise of summer low flows as well as in an increase of runoff peaks. They also state that the increase of low flows after drainage is partially caused by the decline in the water storage which occurs during the first post-drainage months. On a long-term basis, Heikurainen <u>et al</u> (1978) and Heikurainen (1980) conclude that forest drainage has a regulating effect on the flow regime similar to that found for agricultural drainage, reducing runoff peaks and increasing low flows. According to them this long-term leveling effect of drainage on runoff is due to the increased interception of the tree stand and to the higher storage capacity of the peat after drainage. However, Heikurainen (1980) and Ahti (1980) recognize that during long periods of heavy rain, when the interception storage and the storage capacity of the peat are fully restored, runoff peaks may be higher from drained areas than from undrained areas.

The conclusions of Conway and Millar (1960) according to which a network of open ditches creates flashier hydrographs, contrast with the concensus view of the general influences of mole and tile drainage on hydrograph characteristics (Burke, 1975a, 1968; Eggelsmann, 1975). McDonald (1973) commenting on the different results of Conway and Millar (1960) and Burke (1968) suggests that they are a consequence of differences in the peat type and thus on the permeability of the soil of the two studied areas. Sutcliffe (1972), on the other hand, commenting on the different results of Conway and Millar (1960) and Baden and Eggelsmann (1964) states that account should be taken on the different types of drainage involved as well as on the different rainfall patterns of the two sites. Starr and Päivänen (1981) have also recognised the controversy existing in this particular field of research. Although they conclude that forest drainage tends to increase runoff, they also recognize that this influence will depend upon the characteristics of rainfall (or snowmelt), the intensity of drainage, the presence or absence of a tree stand and on the time elapsed since drainage was carried out.

Comparisons between the results of different experiments on peat drainage hydrology are sometimes difficult. Some of the literature in this field may be criticized for not defining clearly the type of peat and the type of drainage involved in the areas studied. Some papers do not even state whether or not the peat was drained (Sutcliffe, 1972). Furthermore most past work is based on comparisons between the outputs of drained and undrained areas. Much less is known about the processes of flow generation in those areas and thus about the reasons why the flow pattern is modified by drainage. This lack of information may lead to speculation on the subject and this is certainly one of the reasons why the sometimes heated discussion about the hydrological consequences of drainage of peatlands, mentioned by Heikurainen et al (1978), has continued for so long. To quote Dooge (1975) on this subject:

"Much of the quantitative information available in published papers suffers from the disadvantage that it is applicable only to the area of study and cannot be interpreted in terms of general principles..... The complexity of topography and of physical properties involved means that empirically derived relationships cannot be avoided. However, to be really useful and to be of significance in comparing one area with another, such empirical relationships must have a sound physical basis".

These comments, drawn to apply either to undrained and drained peatlands, are particularly important in drained peatland hydrology. A similar opinion on research needs in this field is also stated by other authors. To quote Zubets and Murashko (1975):

"Although some progress has been made in the study of the effect of drainage on the water resources of the area, a number of problems have not yet been clarified and require further study. The main aims in this respect should not be just the accumulation of new experimental data; a theoretical examination of the available information should be made to explain the mechanism of the effects of drainage in various hydrological, soil, climatic and hydrogeological conditions."

The study reported in this thesis was undertaken specifically to quantify, and seek an understanding of, the hydrological components and processes operating in a peat area newly drained for forestry purposes. As such its aims were very much in keeping with the recommendations for future research in this field made by Dooge (1975) and Zubets and Murashko (1975). It was felt that such a study might allow, at a later stage, the building of a conceptual model capable of simulating the response and behaviour of this system along the lines suggested by Pilgrim _et al_ (1978). Dooge (1975) and

Zubets and Murashko (1975) have emphasized that an increase in the use of mathematical simulation methods should contribute to an improvement in the understanding of peat hydrology as they have to other hydrological problems.

The thesis falls into 4 Parts. Part 1 comprises this Introduction and the description of the experimental site. Part 2 consists of a detailed description of the methodology and instrumentation used. In Part 3, the results derived from the experimental work are presented. Part 3 is divided into four main sections : the first is concerned with the results obtained for the water balance of the area, the second deals with the results on runoff processes, the third is concerned with a detailed study of the relationship between water table depth and flow rates and, in the fourth, a conceptual model is used as an additional and integrated way of checking the validity of the main experimental findings. Finally, in Part 4, the conclusions drawn from the study are presented.

1.2 The Experimental Site

The work reported in this thesis was carried out on a c.2.5 ha plot located at Leadburn some 17 km south of Edinburgh in South East Scotland (Figure 1). The geographical co-ordinates of the site are approximately 55° 45' N and 03° 13' W (National Grid Reference NT 235 537). The experimental area is on an upland raised bog owned by the Forestry Commission and used by them as a forestry demonstration area. It was selected for the present detailed hydrological study for several reasons as outlined in the following paragraphs.

Firstly, in September 1976, the site was drained for afforestation with the specific objective of facilitating hydrological studies. As Figure 2 indicates the area is surrounded by a deep perimeter ditch leading to a single exit point, which isolates it hydrologically from the surrounding area. Furthermore, in most places outside this perimeter ditch there is an additional ditch, parallel to the previous one, which further assures the hydrological isolation of the site. Similar ways of isolating peat areas have been used in a number of previous hydrological studies (e.g. Calder, 1976; Burke, 1975b; Robertson et al, 1968). The peat in the area is approximately 4 m deep and is underlain by Boulder Clay over Ordovician Shale deposits. The characteristics of the geology together with the low values of the hydraulic conductivity of deep peat layers at the site (Cuttle, pers. comm.), indicate that any vertical or lateral groundwater flow, in or out of

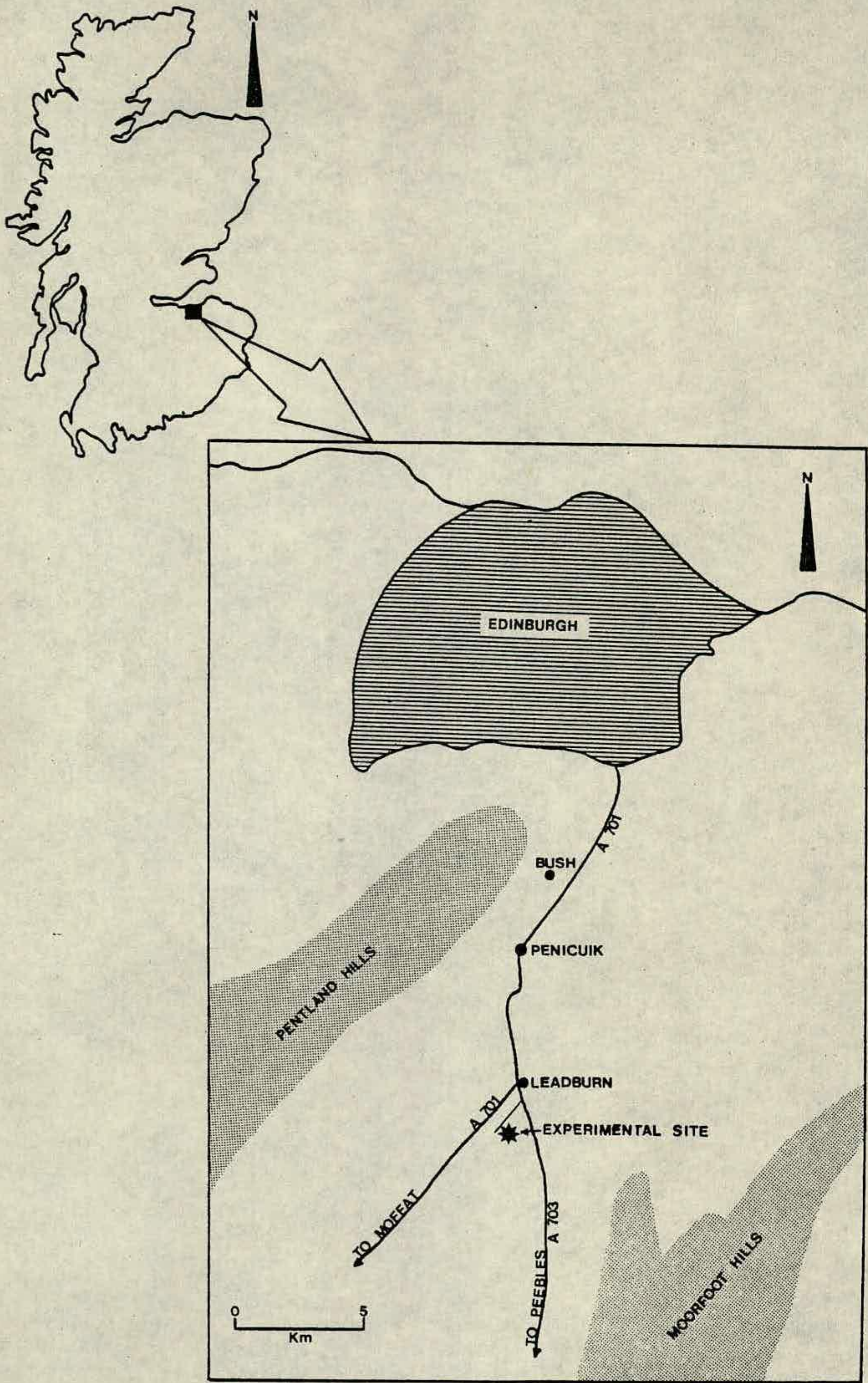


Figure 1 : Map showing the location of the experimental site.

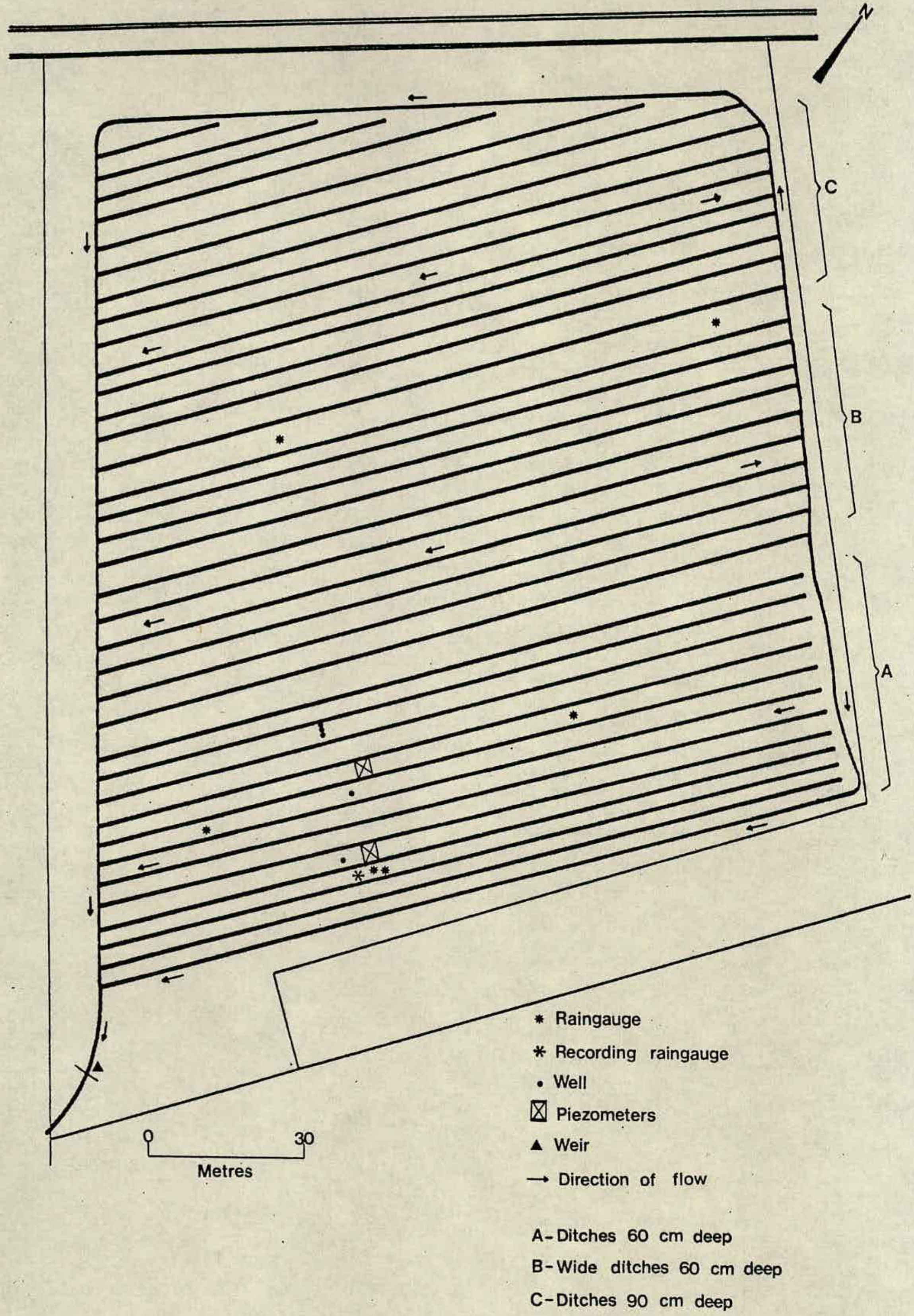


Figure 2 : Detailed map of the experimental area showing the drainage network and the location of the already existing hydrological instruments.

the area, is very unlikely to occur. The area was thus thought to constitute a watertight hydrological system and thus to be an ideal place for an intensive hydrological study on a recently drained peat area.

A second reason for choosing this area was that a certain amount of hydrological information was already available for it. The major elements of the water balance had been monitored continuously since the drainage had been carried out. The hydrological instrumentation existing in the area comprised six weekly raingauges, one recording raingauge and one $\frac{1}{2}$ 90^{o} V-notch weir equipped with a water level recorder (Figure 2). A network of piezometers and measuring wells had also already been established in the area by Dr. S. Cuttle in connection with a proposed fertilizer study, and these were expected to produce much relevant data (Figure 2). Cuttle had also just began to determine the hydraulic conductivity and other physical characteristics of the peat, and other data on these were also available in a report by Fairley (1978). As a result of this work, a lot was known about the origins, natural vegetation and peat characteristics of the bog. The availability of all this background information was thought to constitute a sound and very useful foundation on which to base a detailed hydrological study.

A third attractive feature of the area is that, as Figures 2 and 3 indicate, there are three different types of ditches there: ditches 60 cm deep and with

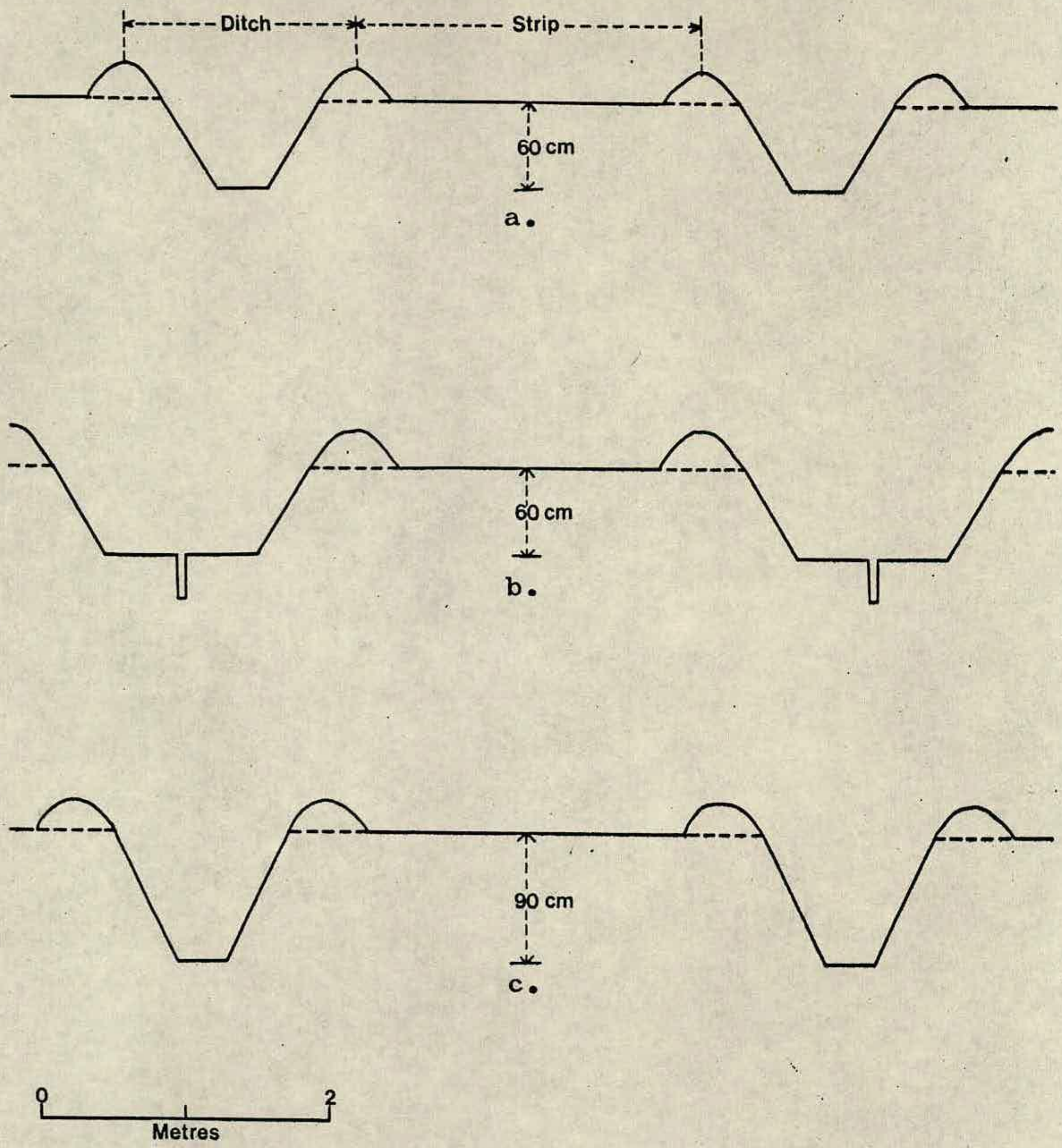


Figure 3 : Cross sections of the different types of ditches in the study area.

a. 60 cm ditches

b. wide 60 cm ditches

c. 90 cm ditches

approximately 4 m of spacing between ditch centres, ditches 90 cm deep with approximately 4.5 m of spacing between ditch centres, ditches 90 cm deep with approximately 4.5 m of spacing between ditch centres and wide ditches 60 cm deep, presenting a 30 cm deep slot in the middle, with approximately 4.8 m of spacing between ditch centres. The presence of different types of ditches in the area was thought to offer interesting possibilities for studies on the influence of drain type on hydrological behaviour.

Fourthly, the study area is not far from Edinburgh and affords easy access to a research worker based in the city. It is also conveniently located near the long term meteorological stations at Penicuik and Bush as Figure 1 shows.

Finally, the area seemed to typify other peatlands liable to be afforested in South East Scotland which it was felt might eventually allow some of the results to be extrapolated to other areas of similar ecological features. It is located at an altitude of 300 m, is relatively flat with a gentle slope to the south and has a relatively wet climate, annual rainfall being around 1000 mm and annual potential evapotranspiration around 400 mm (Fairley, 1978). Snow lies for about 30 days in the year but melts rapidly. The mean winter temperature is about 3.6 ^{o}C and the mean summer temperature 14.7 ^{o}C (Fairley, 1978). The length of the growing season, defined as the number of months with a mean temperature above 6 ^{o}C, is 6 months (Gregory, 1954 cited by Fairley, 1978). The site is very exposed to winds, mainly from the South and West, and gales are frequent.

The peat of the area is composed of an upper layer of poorly humified Sphagnum - Eriophorum peat, overlying a lower layer of highly humified material of similar botanical origin (Cuttle pers. comm.). Before drainage, the dominant vegetation species were Calluna vulgaris (L.) Hull, Eriophorum vaginatum L. and Erica tetralix L. with a discontinuous mat of Sphagnum spp (Cuttle, pers. comm.). After drainage the original vegetation suffered some slight changes, mainly in places where fertilization took place. The planted trees are still small, on average approximately 0.5 m high, and probably have little influence yet on the hydrological behaviour of the area. A general view of the experimental site is shown in Plate 1.

Plate 1 : General view of the experimental site.

PART 2

INSTRUMENTATION AND METHODS

2.1 Water Balance Elements already being Measured

2.1.1 Introduction

According to Donald (1973), the water balance of a catchment area is a concept which considers the processes of motion, loss and recharge of the catchment's water. The quantities of water going through an individual catchment can be evaluated by the so called water balance equation, which is a simple continuity equation of the form:

$$I - O = \pm \Delta S \qquad (1)$$

in which I is the inflow of water to the catchment, O is the outflow of water from the catchment and ΔS is the change in water storage within the catchment. In a watertight area, as the experimental site of this study seems to be, the only inflow of water into the area is from precipitation and the outflow from the area comprises evapotranspiration and runoff (Goode <u>et al</u>, 1977; Romanov, 1968b). In this case the water balance equation can be written as:

$$P - E - R = \pm \Delta S \qquad (2)$$

in which P is the precipitation, E is the evapotranspiration, R is the runoff and ΔS is the change in water storage.

In a complete water balance study all the elements of equation (2) should be measured independently. In most water balance studies, the precipitation and the runoff are measured and the evapotranspiration and the water storage are either measured or estimated. Due to limitations in the data or to the expense of complete data acquisition, published water balance studies are rarely complete (Dooge, 1975).

As was previously mentioned, precipitation, water table variations and runoff had been monitored at the site since drainage had been carried out (see section 1.2 and Figure 2). From April 1980 onwards responsability for these observations was taken over by the author who also carried out all the analyses of the already available data.

The first stage in the investigation was to make a preliminary analysis of the data already being collected to see whether the existing network was adequately measuring the intended hydrological components. In some cases it was found necessary to expand the existing experimental network. All the new instruments were installed and monitored by the author.

This first section of Part 2 deals with the description of previously existing instrumentation of precipitation, water table and runoff as well as with the description of the new instruments installed to improve the measurement of those hydrological components.

2.1.2 Precipitation

Precipitation is one of the most important hydrological elements. The exact determination of the amount of precipitation, its type and the knowledge of its spatial and temporal distributions, governs the reliability of water balance calculations (Toebes and Ouryvaev, 1970).

Precipitation had been measured at the site by a network of six weekly non-recording raingauges and one tilting siphon recording raingauge since March 1977. The non-recording raingauges are standard gauges (Meteorological Office Mk 2) having a collecting funnel with an aperture 127 mm in diameter and standing with their rims 30 cm above ground level. Measurements were taken weekly, each Tuesday, using a calibrated glass measuring cylinder. During winter periods, visits to the site were sometimes difficult due to snow and ice and some measurements had been taken outside the scheduled time. Five of the gauges were installed on the middle of spacings between the ditches, i.e. strips, and one gauge was installed on the top of a ditch ridge, approximately 30 cm higher than the other gauges.

Table 1 shows four separate weeks of typical rainfall readings yielded by the non-recording raingauges, cumulative rainfall values for each raingauge for the period beginning in May of 1977 and ending on April 1979 and the percentage deviations of these cumulative values from the mean of the five gauges installed on the centre of the strips. With the exception of raingauge No. 4, which systematically catches smaller amounts of rainfall, the readings of the different gauges are always very close which indicates a very uniform spatial distribution of rainfall over the area. Raingauge No. 4 was deliberately installed in a higher position, on the top

	Raingauge No.						
	1	2	3	4	5	6	
Period	Weekly Rainfall Readings (mm)						
7/6/77 13/6/77	61.5	65.5	66.8	65.1	68.3	65.5	
19/7/77 25/7/77	6.4	5.8	6.2	5.4	5.7	5.9	
18/7/78 24/7/78	12.1	11.7	12.2	11.0	11.6	11.7	
19/12/78 25/12/78	31.5	32.7	32.2	31.1	33.3	32.4	
	Cumulative Values from 17/5/77 to 24/4/79 (mm)						Mean of Gauges 1,2,3,5 and 6
	1806.7	1759.0	1811.4	1614.3	1753.3	1800.2	1786.1
Percentage Deviation from the mean	+ 1.2%	- 1.5%	+ 1.4%	- 9.6%	- 1.8%	+ 0.8%	

TABLE 1: Sample of rainfall data from the non-recording raingauges.

of a ridge, to study the effect of such exposure on its catch efficiency. Cumulative rainfall caught by this gauge was approximately 10 % lower than the average of the other five gauges. This should be expected as it is known that, due to wind effects, the more exposed a raingauge rim is the lower the rainfall it catches (Rodda et al, 1976; Green, 1970). The network of non-recording raingauges was found quite satisfactory and no changes were thought necessary. To compute the average areal rainfall of the area, data from raingauge No. 4 was ignored and the arithmetic average of the remaining five gauges was calculated on a weekly basis and stored in a computer file.

The recording raingauge already in the area was of the Casella tilting-siphon type with a collecting funnel 203 mm in diameter and with its rim 40 cm above the ground. The instrument was operated on a weekly basis and the chart changed each Tuesday. Frost protection was afforded by putting small amounts of anti-freeze into the collecting chamber of the instrument. It was found that the charts of this instrument could only be read with some accuracy for a minimum time-step of 2 hours. As it was thought necessary to have shorter resolutions during some flood periods, a new rainfall recorder was installed to try to solve this problem.

The instrument chosen for this purpose was a tilting-bucket raingauge recorder (Casella), with a collecting funnel with an aperture of 203 mm in diameter. This was installed in standard fashion with its rim 40 cm above the ground, in June 1979. The bucket tips for each 0.5 mm of rainfall and each tip gives an electric pulse recorded in an 8 channel event recorder (Rustrak). The power supply for the event recorder is constituted by a 12 volt battery. The chart of the event recorder as well as the battery were changed each 2 weeks. During winter periods the water sometimes froze in the buckets of the instrument and under these circumstances data are no longer reliable. This instrument provides a step-wise measure of the rate of rainfall. This set-up gave very useful information during flood periods and times between successive tips of the bucket as small as 1 minute could be measured accurately.

The data from the raingauge recorders were not processed in a continuous way. Rainfall intensities were only computed for periods when flood analysis was required. Raingauge recorders are instruments not supposed to give reliable values of total rainfall amounts over a period of time. The usual procedure for computing rainfall rates is to use the areal average rainfall, computed from standard non-recording raingauges, and then to calculate its temporal distribution according to the data from the rainfall recorders. However in this case when the two rainfall recorders were calibrated against the data from the non-recording raingauges the differences in total amounts of rainfall measured were so small that direct readings from the raingauge recorders were found accurate enough to compute rainfall rates.

It is considered that the final raingauge network provides reliable information on the total amount of rainfall and its spatial and temporal distribution. However, it is important to have in mind that standard raingauges underestimate the true rainfall value, mainly in windy places and during snow periods (Lee, 1980; Rodda et al, 1976; Romanov, 1968b). A raingauge acts as an obstacle to the airflow causing turbulence and eddying just over its rim. As a consequence some rain drops are blown away off the orifice of the gauge which results in the underestimation of the amount of precipitation that would have reached the ground if the gauge had not been there. However, the exact true rainfall is impossible to measure. The most satisfactory approximation of its value is given by a raingauge installed with its rim at ground level (Rodda et al, 1976). Comparisons of catch efficiencies of ground-level and British standard gauges, with their rims 30.5 cm above the ground, have been made in a number of sites in the U.K. Annual catch deficits of standard gauges vary widely in the U.K., being higher in the windy mountainous West and lower in the South East (Rodda et al, 1976). Catch deficits of 3.2 percent (Green, 1970), 6.6 percent (Rodda, 1967) and up to over 20 percent (Rodda et al, 1976) have been reported in the literature. It seems reasonable to assume that, for the present conditions, the catch deficits are unlikely to exceed 6 - 10 percent.

2.1.3 Water Table

The water table is considered a key element in any study on peat hydrology and it can be said that it has been monitored in almost every single work published in this field. Good relationships have been found between water table depths and a number of components of the water balance of peatlands (Goode et al, 1977). Interesting relationships have been found between water table depth and water storage (Heikurainen et al, 1964), between water table depth and runoff (Romanov, 1968b; Chapman, 1965) and between water table depth and evapotranspiration (Romanov, 1968a; Virta, 1966). The key position of water table data in water balance studies of peatlands is particularly emphasized by Romanov (1968a, 1968b), who showed that runoff and evapotranspiration of extensive undrained peatland catchments can be calculated solely from climatic and water table data.

According to Heikurainen (1971), the water table is defined as the water surface that appears in a hole made in the ground. The depth of the water table is the distance between the ground surface and the water table. Water table depth is usually measured in simple boreholes or in standing perforated pipes pushed into the ground. These two systems are generally called wells. According to Heikurainen (1971), the wells must be large enough to ensure that the water surface is not influenced by capillary forces. He also states that the diameter of the well affects the velocity of its response to changes in water relations of the peat: the smaller the diameter of the well, the greater its sensitivity.

As was previously mentioned water table depth had been monitored at the site since drainage had been carried out. This had been done by weekly measurements in five 60 cm deep wells made of pvc perforated pipe with a diameter of 50 mm. Three of these wells were located on the centre of strips between 60 cm deep ditches. The other two wells were located along half of a cross section of a strip and in line with one of the centrally positioned wells. Readings were taken using a battery-operated instrument making an audible buzz when the two terminal electrodes touched the water surface.

A preliminary analysis of the available data showed that the readings from the three wells located on the centre of strips between ditches were fairly consistent with each other, although some differences in response velocities could be noticed (Figure 4). However, some important deficiencies were found in the experimental network. The wells were shallow enough to dry out during dry summer spells, and all these wells were located on strips between 60 cm deep ditches and no data were available on water table levels for areas of site with different types of ditches. Also no data were available on short-term fluctuations in the water table. To overcome these deficiencies, four new wells were installed on the site.

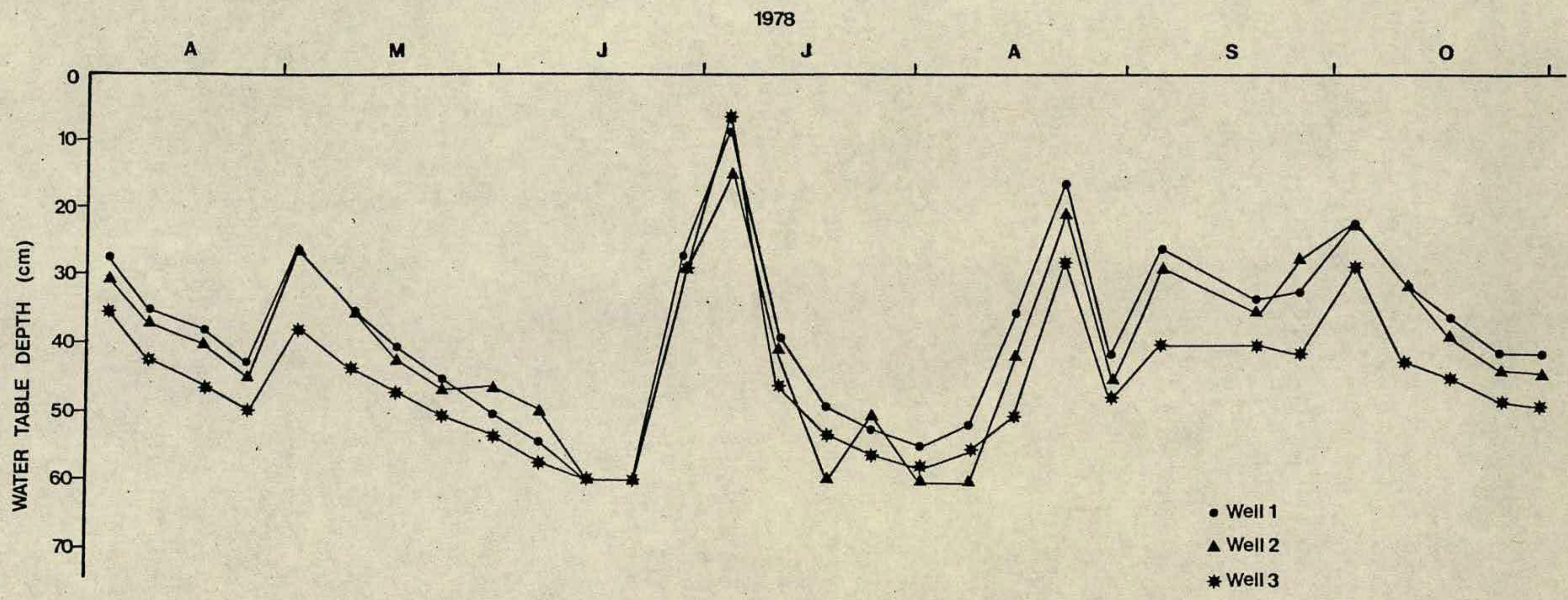


Figure 4 : Sample of data from the three wells located on the centre of strips between 60 cm deep ditches.

To study the influence of ditch depth on the water table level, two new wells were installed on the centre of strips between 90 cm deep ditches. The wells are 90 cm deep and made of perforated pvc pipe with a diameter of 22 mm. A rod, fitting exactly the internal diameter of the pipe, was used to push the pipe into the ground and to keep the interior of the pipe free of soil. This system of installation produces some compression of the peat around the pipe but was found to be the only suitable method for the installation of pipes of such a small diameter. However, the compression is probably small as the diameter of the pipe is also small. Water levels were read once a week using the battery-operated instrument already described.

To monitor short-term fluctuations in the water table two new wells, equipped with water level recorders, were installed on the centre of strips between 60 cm deep ditches (Plate 2). The wells are 90 cm deep and made of perforated pvc pipe with a diameter of 110 mm. The bottom edge of the pipe was sharpened and the pipe pushed into the ground. Soil was removed from the inside using an auger. R. W. Munro IH94 water level recorders were installed for the continuous recording of water level fluctuations. The original floats of the instruments had to be replaced by smaller ones made of sand filled plastic bottles, with a diameter of 90 mm. The gearing wheels of the water level recorders were changed to obtain a suitable scale according to the expected range

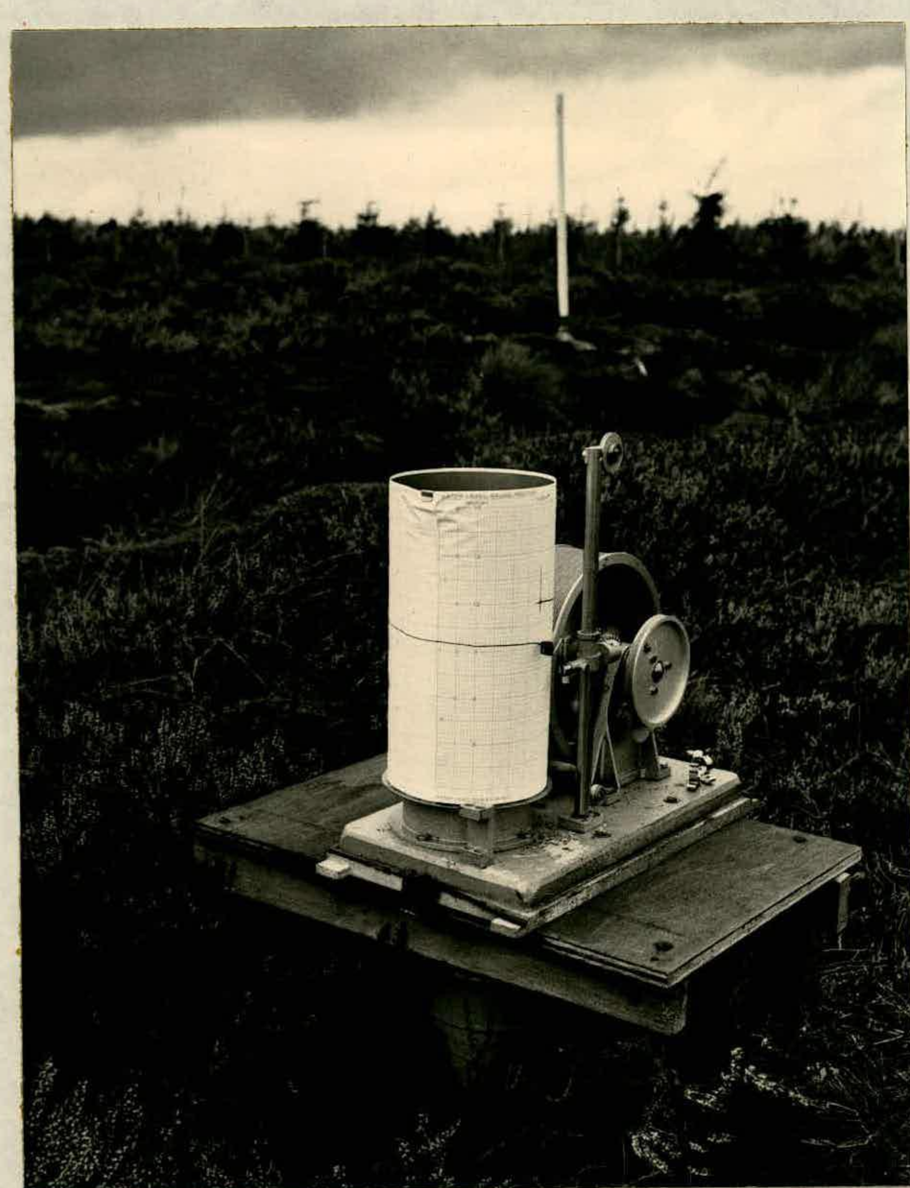


Plate 2 : View of a well equipped with a water level recorder.

of water level fluctuations. When the standard float of the instrument is replaced by a float of smaller diameter deficiencies should be expected in the records obtained (White, 1932). With smaller floats the graph has a step-like appearance, indicating that the movement of the float is spasmodic and lagged behind the movement of the water table. This can be easily explained as it is known from the Archimedes principle that for two different bodies, the water exerts the same upward force when equal volumes of the two bodies are inside of the water. Being so, and assuming a constant mechanical resistance in the instrument, the smaller the diameter of the float the bigger the rise of water needed to overcome this resistance. Some laboratory experiments showed that the spasmodic behaviour of these small floats could be minimised by using floats and wells of close diameters. This procedure was used in this study and the accuracy of the readings is about 0.5 cm. The charts of the instruments were changed weekly and readings were calibrated frequently using a wooden stick, to check the depth of the water table.

Data collection from the three existing wells, located on the centre of strips between the 60 cm deep ditches was continued and these wells provide the main available information on long-term water table fluctuations in the area. Data from these wells were stored, on a weekly basis, on computer file. Data from the two wells monitoring water table levels of areas with deeper drains, were stored in a different computer file. The charts of the water level recorders were only digitalized for periods when short-term water level analysis was required.

The final experimental network on water level, consisting of nine wells, gave relevant information either on long-term and short-term water table fluctuations within the area. The experimental network is denser in the area drained by 60 cm deep ditches as these constitute the most common type of forest drainage schemes used in South East Scotland.

2.1.4 Runoff

Runoff is the major hydrologic output from the area. Water outflow had been measured by a $\frac{1}{2}$ 90° V-notch weir equipped with a water level recorder since March 1977. The weir is located at the outlet of the perimeter ditch and was installed according to the recommendations of the British Standards Institution (1965). Accumulation of grass and peat on the V of the weir was prevented using a filter made of coarse net. The chart of the water level recorder was changed weekly.

The gauge datum was frequently checked by levelling to avoid systematic errors in stage readings due to the settlement of the peat around the instrument. Rates of flow were computed from the stage records using the stage-discharge equation recommended by the British Standards Institution (1965). The computed flows were checked regularly against exact flow values measured using a stop watch and a collecting vessel of known volume. A reasonable agreement was found between computed and measured flows with some exceptions for very low stage values when errors sometimes arose from fouling of the V-notch by small pieces of vegetation. Errors also occured during some winter periods due to water freezing in the channel and/or in the float well under the water level recorder. In these circumstances the stage records are no longer reliable.

The stage records were digitalized on an hourly basis and stored in a computer file. A simple computer program was produced to convert these readings into flow rates. The hourly flow rates were used to compute flow amounts for different time-steps, according to the requirements of data analysis.

The existing experimental layout seemed to provide reasonably accurate data during frost-free periods and no instrumental improvements were thought necessary in this aspect of the study.

2.1.5 Section Conclusion

From the considerations of the previous sections it seems that the improved experimental network gives reliable information on rainfall, water table and runoff.

Some preliminary analyses of the available data showed, however, that other hydrological components and processes should also be monitored for a better understanding of the hydrological behaviour of the system. In particular detailed experimental work was thought necessary on evapotranspiration and flow components. The following sections deal with the description of the instrumentation and methods used for these aspects of the investigation.

2.2 Detailed Measurements and Estimates of Evapotranspiration

2.2.1 General Description of the Methods Used

As can be seen from the already presented equation (2), evapotranspiration is an important component of the water balance.

Evapotranspiration can be estimated or measured directly by a wide variety of methods and instruments that have been reviewed in a number of published works (Rodda et al, 1976; Ward, 1975; World Meteorological Organization, 1974, 1971; Toebes and Ouryvaev, 1970; Romanov, 1968a, 1968b). In the present work, four different methods were selected to estimate and measure evapotranspiration in the study area. These are discussed in the following paragraphs.

The use of the water balance method for the estimation of the actual evapotranspiration of the site was an obvious solution as data on rainfall, runoff and water table depth were already being collected in the area. In this method the already described water balance equation (see 2.1.1) is solved and evapotranspiration is calculated as the only unknown parameter. In the present case rainfall and runoff are measured directly and water table depth data can be used as an index of variation in water storage (Romanov, 1968a, World Meteorological Organization, 1971). For periods when the initial and final water table levels are the same, variation in water storage can be assumed to be zero (Romanov, 1968b) and equation (2), defining the water balance of watertight areas, can be further simplified and written as :

$$E = P - R. \tag{3}$$

Equation (3) is usually used to compute actual evapotranspiration on an annual basis since water storage and water table levels can be assumed to have similar values at similar times of the year (Romanov, 1968b; Donald, Gordon and Wigham, 1973). Even if this assumption is not completely true, the errors involved usually have a negligible influence on the estimated values of annual evapotranspiration (Romanov, 1968b). In the present study, equation (3) was used to compute actual evapotranspiration for periods having similar initial and final water table levels. It is generally accepted that the water balance method gives fairly reliable estimates of actual evapotranspiration, although it is recognized that the results of the method are affected by the already described errors involved in rainfall and runoff measurements (Ward, 1975).

Actual evapotranspiration data are usually compared with potential evapotranspiration values to see whether soil moisture, vegetation characteristics and other environmental conditions are somehow keeping actual evapotranspiration below its potential value. In this study potential evapotranspiration was estimated using data from a sunken pan, with a diameter of 2 ft, installed at the Bush meterological station some 10 km away and by the Penman formula using meteorological information from Penicuik and Bush. The Penman formula is a combination of the energy balance equation and the aerodynamic equation which uses meteorological data as input. The formula is described in a number of publications and textbooks (Penman, 1963, 1956; Ward, 1975; Ministry of Agriculture, Fisheries and Food, 1967) and has the general form of :

$$E = (\frac{\Delta}{\gamma} H + Ea)/(\frac{\Delta}{\gamma} + 1) \qquad (4)$$

where E is the evapotranspiration (mm/day), Δ is the slope of the saturated vapour pressure (mm Hg/^{o}F), γ is the psychrometric constant (0.27 mm Hg/^{o}F), H is the net radiation energy (mm/day) and Ea is an expression for the drying power of the air involving wind speed and saturation deficit (mm/day). In the calculations of the Penman potential evapotranspiration a reflection coefficient of 0.25, typical for short green crops (Ward, 1975), was used in the computation of H. The Penman formula was selected among a large number of other possible formulae, as it is the standard way of estimating potential evapotranspiration in Britain (Ministry of Agriculture, Fisheries and Food, 1967), and because it has been successfully tested in Britain and in other parts of the world (Rodda et al, 1976; Ward, 1975; Stanhill, 1961). The use of pan evaporation data and meteorological information from Bush and Penicuik was thought to give a quite satisfactory estimate of the potential evapotranspiration for the site as this hydrological component is usually regarded as a conservative phenomenon (Ledger and Thom, 1977; Rodda et al, 1976), with little variation in space and time, and the two mentioned meteorological stations are near the site (see 1.2) and have exposures and altitudes, respectively of 189 m and 184 m, that do not differ much from those of the experimental site. Furthermore during all the present work, care had to be taken to keep a balance between the accuracy of the measurements needed and the work that could actually be undertaken by a single person. For this last reason, more sophisticated formulae, such as the Penman-Monteith formula (Monteith, 1973), which involve more detailed and time consuming measurements, were not considered possible in the present study.

The previous two methods provide estimates for the actual evapotranspiration of the site and for its potential value. However, drainage for forestry purposes creates great disturbances in the homogeneity of the ground surface and, as a consequence, two main types of ground surface are originated which probably have different evapotranspiration rates. In fact a recently drained peatland can be broadly divided into 2 parts:

1. The vegetated areas occupied by the strips between the ditches.

2. The ditch areas, occupied by the slopes and bottoms of the ditches, with almost no vegetation and sheltered from climatic conditions.

Appreciation of the fact that the area consists of these two very different component parts is fundamental for an understanding of this thesis. Therefore it is perhaps now the proper time to emphasize that for brevity of expression these two areas will be respectively called as strips and ditches throughout this thesis. As the ditch areas have almost no vegetation cover their water losses to the atmosphere will be mainly constituted by evaporation from the soil. The area occupied by ditches is quite a significant proportion of the total area. It was possible to measure, from a detailed survey of the site, that approximately 30 % of the total area consists of ditches and 70 % of strips. Actual evapotranspiration from the whole area can be expressed as a weighted mean of actual evapotranspiration from these two component parts:

$$EP = \frac{AD \times ED + AID \times EID}{AD + AID} \qquad (5)$$

where EP is the evapotranspiration from the whole area (mm), ED is the evaporation from the ditches (mm), EID is the evapotranspiration from the strips (mm), AD is the area occupied by ditches and AID is the area occupied by strips. A similar equation was used by Romanov (1968b) to express evapotranspiration from undrained bogs as a weighted mean of evapotranspiration from its two component areas, i.e. ridges and pools. If the overall actual evapotranspiration is known and actual evapotranspiration from one of the component areas is measured separately, equation (5) can be used to estimate actual evapotranspiration from the remaining area.

To try to solve this problem two methods were selected for the separate measurement of actual evapotranspiration from the strips: the water table fluctuations method and the evapotranspirometer method.

Water Table Fluctuations Method

The calculation of evapotranspiration from water table fluctuations is well exemplified in the classic paper of White (1932). This method was later applied to the estimation of evapotranspiration from forests on drained peatlands (Heikurainen and Laine, 1974; Heikurainen, 1963, 1971). According to Heikurainen and Laine (1974), the daytime fall of the water table can be used to estimate daily evapotranspiration during rainless days. They found that the water table fall begins in the forenoon and goes on until 6 - 8 h p.m.. During the night, the water table may behave in different ways depending on the prevailing soil water conditions (Figure 5): it may drop (Figure 5a) if there is any outflow from the area concerned; it may rise (Figure 5d) if there is an inflow to the area from the surroundings; or it may remain unchanged (Figure 5b) if there is neither inflow nor outflow, in or out of the area. The diurnal fluctuation of the water table is delayed and no distinction is possible between daytime and nightime rate of fall if the water table is at a deep level (Figure 5c).

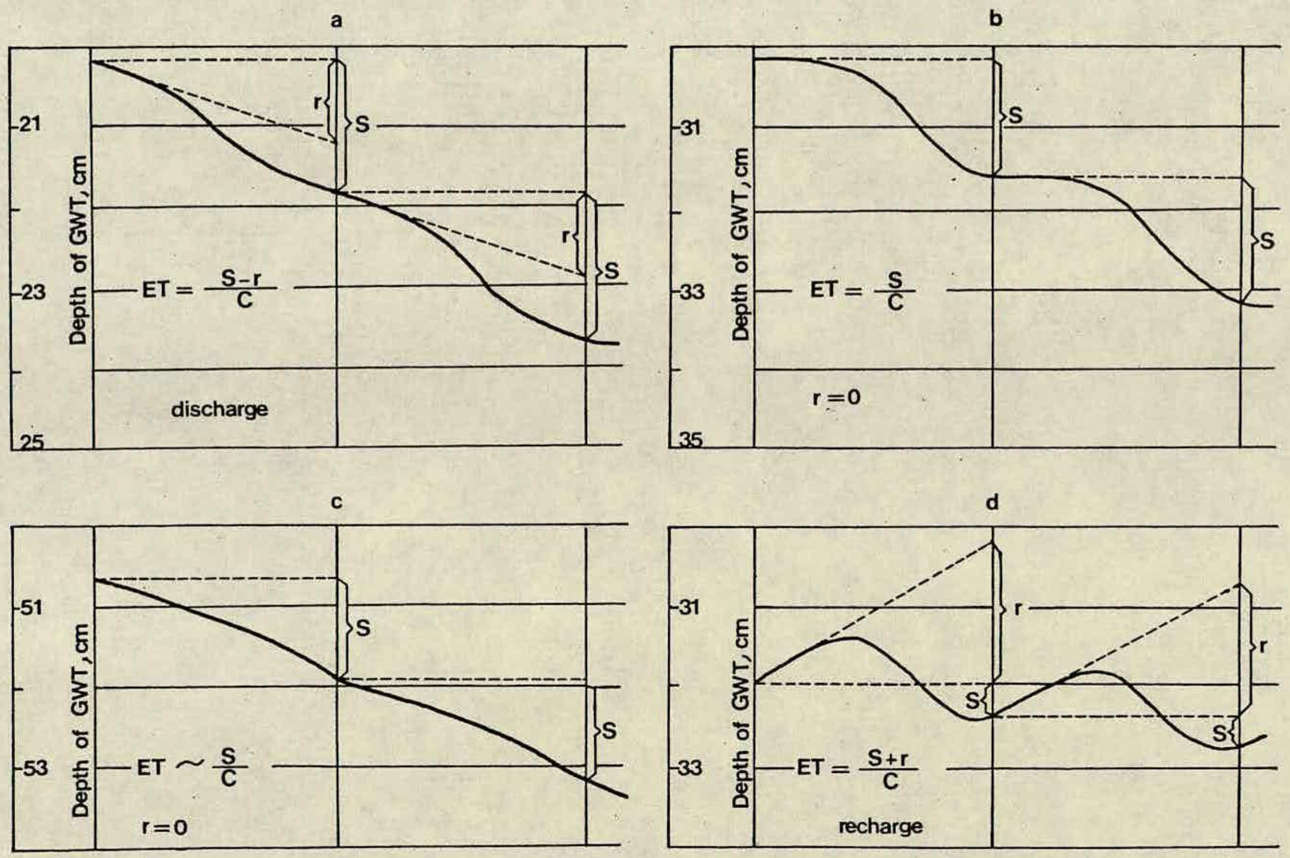


Figure 5 : Types of behaviour of the groundwater table (after Heikurainen and Laine, 1974).

Diurnal evapotranspiration can be calculated in accordance with Figure 5 using the formula:

$$ET = (S \pm r)/C \qquad (6)$$

in which ET is the diurnal evapotranspiration, S is the diurnal total drop of the water table, r is the extrapolated drop(-) or rise(+) indicated by the sequel of night time water table change and C is the groundwater coefficient of the soil, defined as the ratio between the fall (or rise) of the water table and the amount of water causing it. Equation (6) can also be expressed in the following form (Ward, 1975; White, 1932):

$$ET = (S \pm r) \times Sy \qquad (7)$$

in which Sy is the specific yield of the soil, defined as the amount of water needed to be removed (or added) to cause a unit fall (or rise) of the water table. The specific yield is simply the inverse of the groundwater coefficient of Heikurainen and Laine (1974). According to Ward (1975), the main disadvantage of the method is the large number of variables that may affect the water table fluctuations, some of which, e.g., groundwater inflow into the area, are difficult to determine with high accuracy. Furthermore, Callede <u>et al</u> (1978) argued that the rise of water level during the night may happen without any inflow from the surroundings and that it can be explained solely from consideration of the principles of soil water physics. In the present study data from the wells equipped with water level recorders (see 2.1.3) were expected to be used for the application of this method. However, some difficulties arose and, as will be explained in Part 3, this method seems to be inapplicable in our experimental area.

Evapotranspirometer Method

Evapotranspirometers, according to the World Meteorological Organization (1971), are instruments for measuring the evapotranspiration consisting of a sunken tank, filled with soil and having the same vegetative cover as the adjacent area, from which the water loss is measured by weighing, or by accounting for all incoming water at the surface and all outflow from the bottom of the tank. Lysimeters, also according to the World Meteorological Organization (1971), are a special type of evapotranspirometer designed to permit the measurement of water draining through the soil. Some confusion can be noticed in the literature in the use of these two terms. To overcome this problem in the present work the term lysimeter will be used from now on, according to the criterion of Ward (1975), to identify evapotranspirometers used to measure actual evapotranspiration. Lysimeters have been widely used to measure actual evapotranspiration from different soils, different vegetation types and different moisture regimes. A number of literature reviews are available on the design and operation of these instruments (World Meteorological Organization, 1974, 1971; Toebes and Ouryvaev, 1970; Romanov, 1968a). Evapotranspiration is computed from lysimeters as the only unknown parameter on the water balance equation of the soil-vegetation sample isolated in the lysimeter tank.

Lysimeters have been widely used to measure evapotranspiration from peatlands (Romanov, 1968a; Ivitskii, 1968a, 1968b; Virta, 1966). In most of the previous works water table level was controlled inside the lysimeters, to study its influence on the actual evapotranspiration. Boelter (1972a), Sturges (1968a) and Bay (1966) used a special kind of lysimeters, termed by Bay as evapotranspirometers, made of bottomless tanks. This technique assumes that, due to the very low hydraulic conductivity of deep peat layers, a bottomless tank pushed into the ground isolates, hydrologically, the sample of peat which remains in its interior. In some cases this assumption proved not to be valid (Boelter, 1972a).

To be reliable, evapotranspiration measurements from lysimeters must meet a number of requirements (World Meteorological Organization, 1971; Toebes and Ouryvaev, 1970; Romanov, 1968a). The area of the lysimeter should be sufficiently large to give a representative vegetation cover and to minimize the disturbances due to the walls. The soil sample should be as undisturbed as possible and the moisture conditions, in the interior of the lysimeter tank, should be similar to the ones of the surrounding area.

Lysimeters used in past work vary widely in their size and design. Lysimeter tanks with exposed areas as big as 5 m^2 and as small as 0.05 m^2 are reported in the literature (World Meteorological Organization, 1971; Toebes and Ouryvaev, 1970). In the present study, small lysimeters, with an exposed area of 0.032 m^2, had to be chosen to allow a single person to install and operate them with ease. Although it is recognized that small lysimeters are less representative of the behaviour of the surroundings (World Meteorological Organization, 1971; Toebes and Ouryvaev, 1970; Romanov, 1968a), they have the advantage of being easily replicated and are usually suitable for short duration research projects (Toebes and Ouryvaev, 1970). In the present work five lysimeters were used. These lysimeters had to be of low cost and of a design that would allow their construction within the resources of the available workshop facilities. A simple and economic type of lysimeter (Ingram, pers. comm.), which fulfils the outlined requirements, was selected for the present study. In this type of lysimeter, water storage changes are measured by a manometer connected with an inner tube filled with anti-freeze on which the lysimeter tank rests. A similar approach to weighing soil monoliths was successfully used by Nichols and Brown (1980), Forsgate et al (1965), Winter (1963, 1962) and Glover and Forsgate (1962). The main aspects of the design and operation of the lysimeters are described below.

2.2.2 The Lysimeters

The constructional details of the small weighing lysimeters used in the present work are shown in Figure 6. The apparatus comprises a soil container, a weighing device and a drainage system.

The soil container consists of an inner cylinder, 45 cm deep, made of pvc pipe with an internal diameter of 20.2 cm. This inner cylinder houses an undisturbed peat monolith which is underlain by a shallow layer of coarse sand, approximately 3 cm deep. The water table level is monitored inside the inner cylinder by a small well made of perforated semi-rigid tube with a diameter of 7 mm. The soil container is sealed by a circular pvc sheet at the bottom and the only outlet from it is a small pvc pipe, with a diameter of 23 mm, which connects with the drainage system. The inner cylinder is supported by a hospital car inner tube filled with anti-freeze, connected by a semi-rigid tube to a glass measuring column. This column is attached to a meter scale and is protected from thermal effects by a removable cover made of perforated white pvc pipe. All tube connections were tested against leakage. The inner cylinder and the inner tube which supports it, are housed in an outer cylinder, 65.4 cm deep, made of pvc pipe with an internal diameter of 30.6 cm. In the bottom of the outer cylinder a small pvc pipe, with a diameter of 23 mm, allows the drainage system to cross its wall. A collar of pvc pipe, fitting

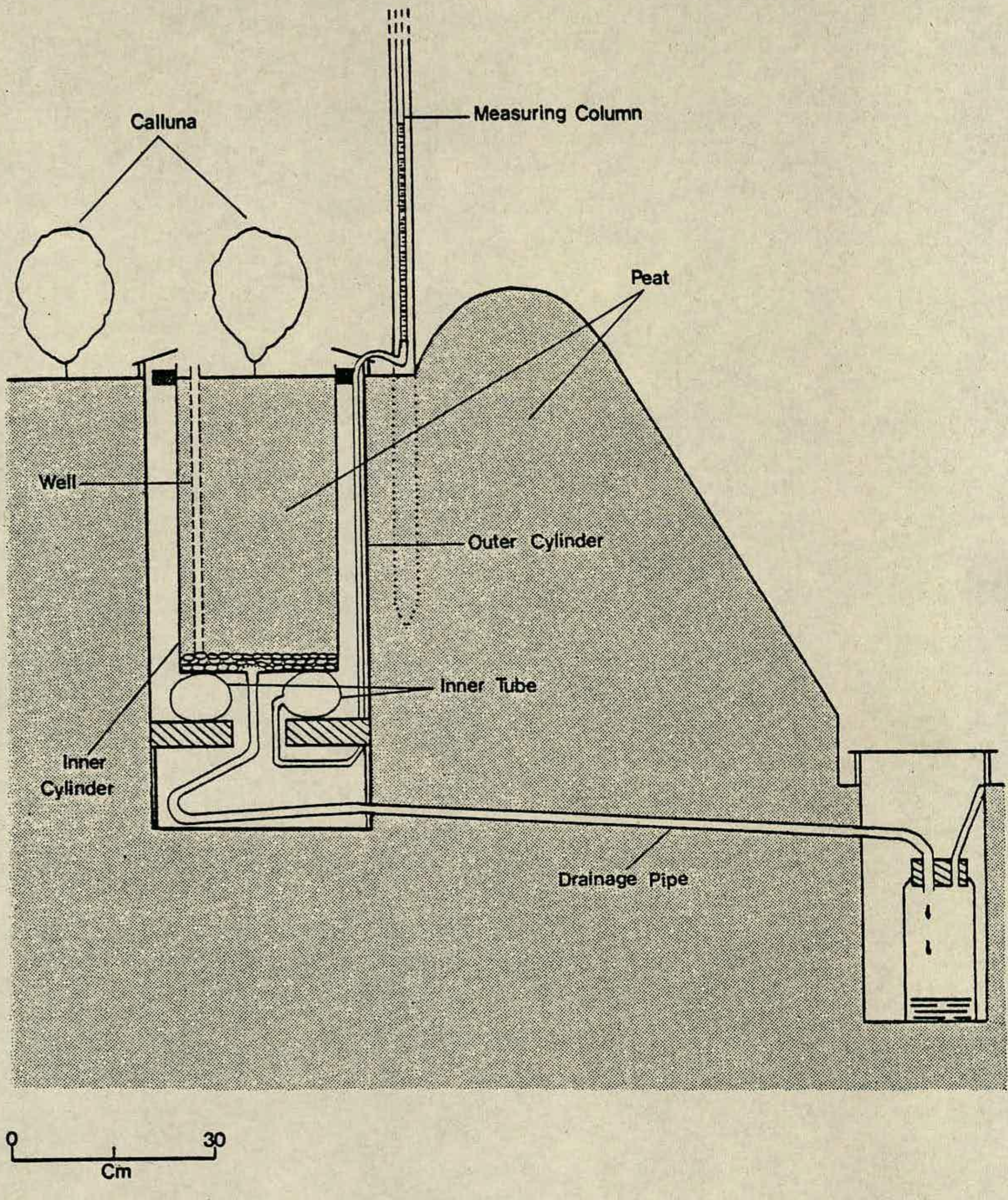


Figure 6 : Diagram showing the constructional details of the lysimeters used.

exactly the inside of the outer cylinder holds the wood support of the weighing system. This wood support is a circular piece of plywood with a hole in the middle to allow the passage of the drainage tube and of the semi-rigid tube of the hydraulic weighing system. The dimensions of all the components of the apparatus which remain inside the outer cylinder are such that the surface of the soil monolith is level with the ground surface outside the lysimeter. The inner cylinder has four lateral wood projections on its top to hold it safely in position, preventing shaking due to wind, and allowing it to be lifted for inspection. A removable annular roof, made of green painted galvanized iron, shelters the clearance between the walls of the inner and outer cylinders. The drainage outlet from the inner cylinder is connected by pipe to a collecting vessel housed in a pvc cylinder which is buried in the bottom of the nearby ditch. The drainage pipe from the inner cylinder is protected by two filters: one of coarse sand, the other of thin wire mesh. All connections between different sections of the drainage system were tested against leakage. When the drainage system is blocked, a suction can be applied to the drainage vessel, using a suction pump. Plate 3 shows the final view of an installed lysimeter.

Two lysimeters allowing free drainage were installed in June 1979. These were used as a preliminary experiment to see whether the system was suitable for the purposes of the present study.

Plate 3 : Final view of an installed lysimeter.

The critical points in the installation of the lysimeters are obtaining an undisturbed soil-vegetation sample and sealing the bottom of the inner cylinder. The undisturbed soil monolith was obtained using a removable blade attached to the inner cylinder bottom. During installation care was taken that at least one plant of Calluna vulgaris remained in the vegetation sample, as it seems that after drainage this species dominates the vegetation of the area. The fact that Calluna vulgaris becomes the dominant species after drainage has also been recognized on other Scottish peatlands (Department of Agriculture and Fisheries for Scotland, 1964, 1965). Full details on the installation of the lysimeters are given in Appendix 1.

Calibration of the weighing system of the two installed lysimeters was done in situ, during each visit to the site: known weights were put on the top of the soil sample and corresponding changes in the measuring column were read. Although it is recognized that calibration of this type of system is not precisely linear (Winter, 1963), due to distortions of the inner tube and thus to changes in the contact area when the soil monolith weight varies, deviations from linearity were found to be so small that the linear approximation was used in the present study. The factors for change in water storage in mm per mm of measuring column height were respectively 0.74 and 0.78 for the two lysimeters. Laboratory tests showed that the weighing hydraulic system takes some time to stabilize and to give accurate results. In fact the measuring column height decreases during the first week and then stabilizes, when the inner tube is initially put under a constant weight. For this reason the first week of readings after the installation of the lysimeters was ignored.

The measuring column heights and the drainage from the lysimeters were measured twice a week, on Tuesdays and Fridays. Evapotranspiration was computed solving the water balance equation for the soil monolith which can be written as:

$$E = P - D \pm \Delta S \tag{8}$$

in which P is the precipitation, D is the drainage from the lysimeter and ΔS is the variation of the water storage which is computed using the formula:

$$\Delta S = \Delta L \times CF \tag{9}$$

in which ΔL is the variation of measuring column height and CF is the factor to convert measuring column change into water storage change. The values of precipitation used were those computed from the five non-recording raingauges (see 2.1.2).

Figure 7 shows cumulative evapotranspiration data obtained during the first season of observations, from July to October 1979. Data from the lysimeters were compared with pan evaporation obtained from the Bush meteorological station. Figure 7 shows that cumulative evapotranspiration from the two lysimeters follows closely the cumulative pan evaporation during the first part of

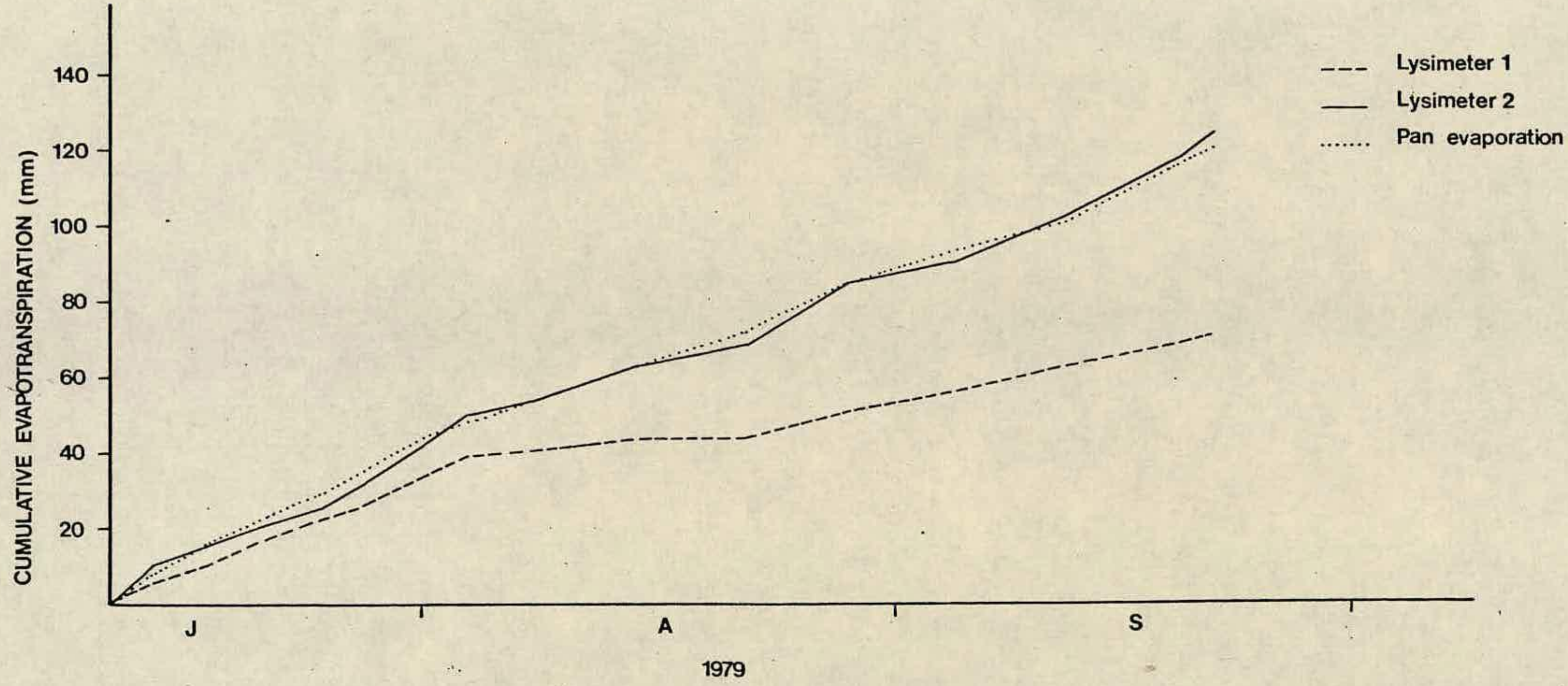


Figure 7 : Cumulative evapotranspiration from lysimeters 1 and 2 and cumulative pan evaporation during the growing season of 1979.

the period. However, lysimeter 1 began to underestimate drastically the potential evapotranspiration in the beginning of August after a heavy rainfall event. It was noticed that from then on lysimeter 1 was not draining properly and that the soil sample remained waterlogged for long periods. This was causing evident physiological disturbances to the Calluna plant reflected by its purple colour. This purple colour usually only occurs after the first frosts of October (Watson et al, 1966). It was thought reasonable to assume that the divergence of cumulative evapotranspiration curves from the two lysimeters during the final part of the observation period was due to disturbance of the transpiration rate from lysimeter 1.

As it is known that transpiration is strongly dependent upon stomatal conductance of plant leaves (Jarvis and Stewart, 1979), this assumption was tested by measuring stomatal conductance of Calluna shoots on each of the lysimeters and on the surrounding area. This was done using a diffusion porometer and the method of calculation described by Beardsell et al (1972). In the calculations the leaf area was taken as the projected area of each shoot. Stomatal conductance was calculated for three Calluna shoots in each lysimeter and for four Calluna shoots in the surrounding area. Average values for each lysimeter and for the surrounding area are shown in Figure 8. This indicates clearly that the lower evapotranspiration values observed in lysimeter 1 are due to

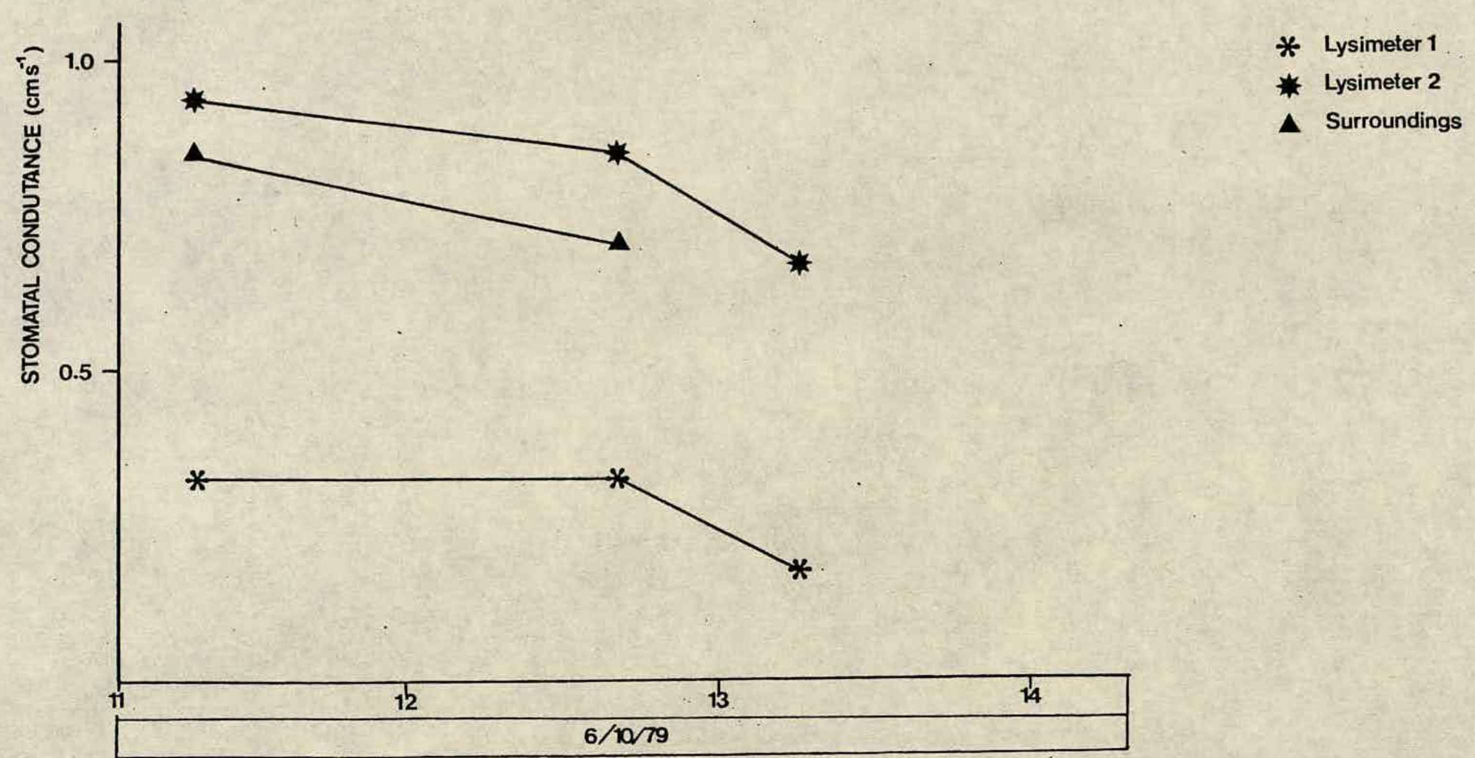


Figure 8 : Stomatal conductance of <u>Calluna</u> shoots measured on lysimeter 1, lysimeter 2 and surrounding area on October 10, 1979.

lower stomatal conductance of its Calluna leaves and thus to the lower transpiration rates from its vegetation sample. The fact that the Calluna plant of the well drained lysimeter 2 shows more physiological vigour than the Calluna plant of the waterlogged lysimeter 1 should be expected as it is known that luxuriant Calluna - dominated heaths develop when peat soils are dryed-out and aerated (Gimingham, 1972). The close agreement between evapotranspiration data from lysimeter 2 and pan evaporation (see Figure 7) indicates that even in a freely drained peat sample evapotranspiration is not restricted below its potential value. This being so the surrounding areas of the strips between ditches, which have much more favourable moisture conditions, should be also evapotranspirating at potential rates.

To provide a further check on the encouraging results obtained during the first season of observation, three more lysimeters were built and installed during the following season (from April to October 1980). These new lysimeters have the same dimensions and the same design as the earlier ones. Although some thought was given to controlling water table levels inside these new instruments, the encouraging results obtained from the freely drained lysimeter during the preliminary experiment suggested that it would be more reasonable to keep to the free drainage design.

When lysimeter data are analysed, the errors involved in the measuring technique used must be taken into account. These errors can be divided into four categories: errors due to lack of representativeness; errors due to temperature, atmospheric pressure or evaporation effects on the measuring column readings; errors due to leakage and errors on the precipitation input measurement.

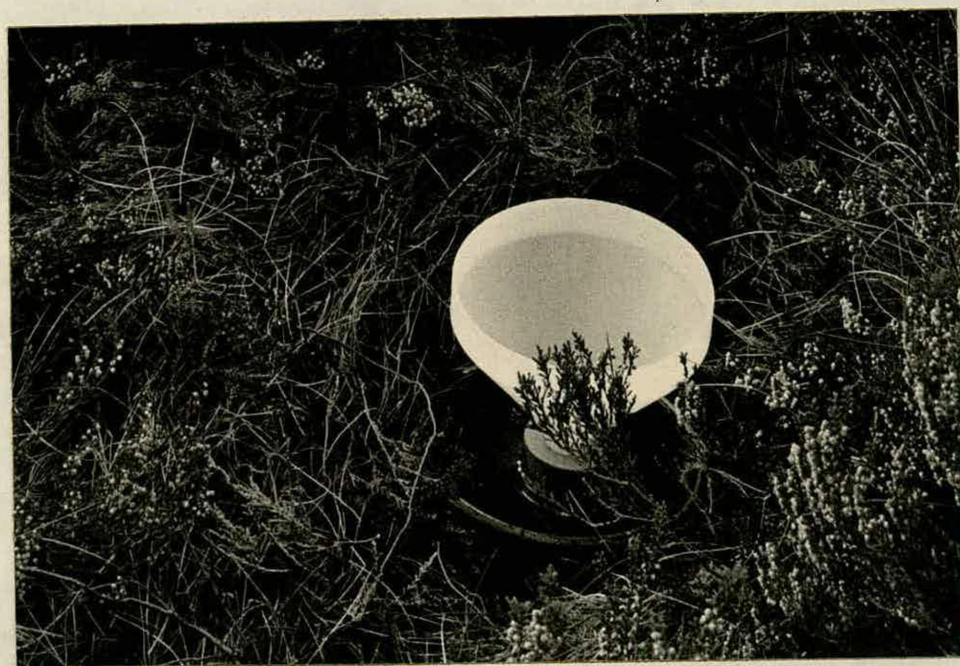
The World Meteorological Organization (1971) and Romanov (1968a) have discussed at length the shortcomings, due to lack of representativeness of the lysimeter method. These shortcomings may be briefly divided into four categories: difficulties in having a representative vegetation sample; difficulties in keeping similar moisture contents inside and outside the lysimeter; disturbance of the thermal conditions of the soil monolith due to wall and base effects; and difficulties in having an undisturbed soil monolith and in eliminating the wall effects on drainage. Most of these shortcomings, with the exception of moisture conditions and the nature of the soil monolith, are particularly important in small lysimeters and can only be overcome when their size is substantially increased. In the present case the lysimeters were deliberately kept with moisture contents lower than the surroundings. Allowing free drainage means that the lysimeters do not reflect the influence of water table depth on evapotranspiration. If it is found that evapotranspiration is not restricted in the soil-vegetation sample when free drainage is allowed, it certainly means that the surroundings, where moisture conditions are more favourable, are also evapotranspirating at the potential rate. As was previously seen encouraging results in this respect were found during the first season of observations.

It must be recognized that the hydraulic weighing system may be affected by changes in temperature that can cause changes in the volume of the manometric liquid. However as the inner tubes are installed 50 cm below the ground surface little temperature effect should be expected in the measuring column readings (Winter, 1962; Glover and Forsgate, 1962). Also as was previously described, the measuring column is protected against radiation by a white plastic cover. Furthermore, the part of the weighing system outside the outer cylinder was replicated and readings from this new system were used to correct any changes in the measuring column that might be due to temperature. To minimise temperature effects on the results, readings were always taken at a standard time, early in the morning, according to the recommendations of Glover and Forsgate (1962) and Forsgate et al (1965). Evaporation from the meniscus of the measuring column was avoided by keeping it sealed at the top, between readings, by a tight rubber cover. Atmospheric pressure has no influence on the weighing system since pressure is the same on the top of the soil monolith and on the meniscus of the measuring column (Glover and Forsgate, 1962).

All lysimeters were frequently checked against leakages in both the drainage and the weighing systems.

No such leakages were found in any of the installed lysimeters during the whole period of observation.

Errors on the estimation of evapotranspiration can occur if the precipitation input is not correctly measured. During some periods, under conditions of heavy rain and high wind velocity the water balance of some lysimeters yielded negative values of evapotranspiration. According to Rijtema(1965) this indicates that measured rainfall amounts underestimate the true rainfall. He found this same problem even when precipitation was measured at ground level. However, it should be expected that possible errors in rainfall measurements would influence the results of all lysimeters and not only some as was the case in the present study. The fact that only some lysimeters showed this behaviour tended to indicate that some of them were working as rainfall traps. This hypothesis was thought to be a feasible one as it was noticed that the lysimeters that were giving negative estimates of evapotranspiration had vegetation samples standing well over the rim of the inner cylinder. The lysimeters with shorter vegetation never gave any negative estimates of evapotranspiration. The validity of this hypothesis was tested by simulating the behaviour of the lysimeters using two hand made raingauges, described by Yesilkaya (1979), having a collecting funnel with a diameter of 152 mm and with their rims approximately at ground level. In one of these gauges a Calluna plant was inserted into the funnel in such a way that it was standing well over its rim. The other gauge was set up as a normal ground level raingauge (Plate 4). The positions of the two gauges were moved from time to time to detect any influence of the positioning of the gauge on the amounts of rainfall caught. Table 2 shows a sample of data from these gauges together with the areal rainfall and with evapotranspiration computed from areal rainfall for two lysimeters, one with taller vegetation and the other with shorter vegetation. Table 2 shows clearly that the ground level raingauge with the plant of Calluna tended to catch much more rain than the normal ground level raingauge and that this was normally accompanied by a negative evapotranspiration estimate from the lysimeter with taller vegetation. Although there is no doubt that some of the lysimeters were working as rainfall traps, quantitative corrections for this effect were impossible to make as it is known that rainfall distribution over the surface of unlevel ground depends on the direction and inclination of the rain and on the slope and aspect of the ground (Fourcade, 1942), which are factors that vary from storm to storm and from lysimeter to lysimeter. The effect of trapped rainfall was corrected in the lysimeter data by assuming that lysimeters which behaved in the same way during rainless periods would also behave in a similar fashion during rainy periods. During rainy and windy periods data from lysimeters with taller vegetation were ignored and data from lysimeters with shorter vegetation were generalized to all lysimeters.



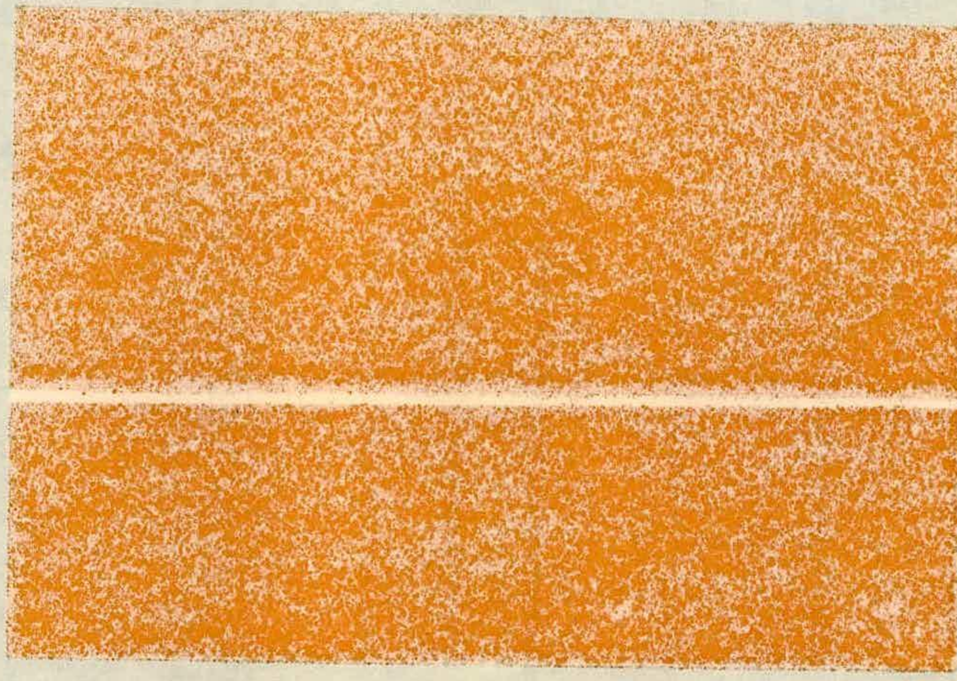
(a)

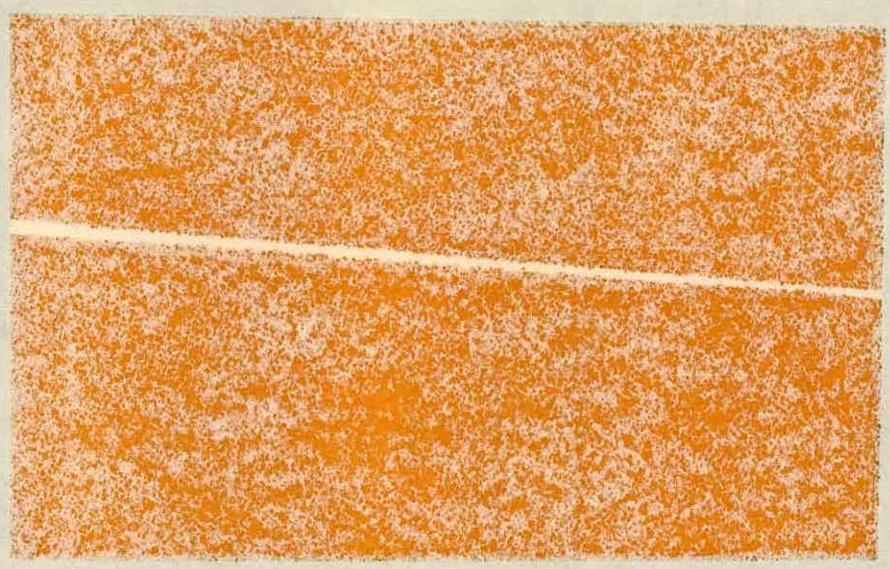
(b)

Plate 4 : Ground-level raingauges used to simulate the influence of the vegetation cover on the amounts of rainfall caught by the lysimeters.

(a) ground-level raingauge

(b) ground-level raingauge with a Calluna plant inserted into the funnel.





Period	Ground-level raingauge (mm)	Ground-level raingauge with Calluna (mm)	Areal Rainfall (mm)	Evapotranspiration (mm)	
				Lysimeter with taller vegetation	Lysimeter with shorter vegetation
1/8/80 5/8/80	44.1	59.5	42.0	- 19.6	0.7
5/8/80 8/8/80	21.2	32.8	22.0	4.7	5.9
8/8/80 12/8/80	11.0	11.8	9.0	6.1	8.3
12/8/80* 15/8/80	20.4	27.6	20.0	- 5.1	4.4
15/8/80 19/8/80	1.0	1.0	1.4	19.3	13.9

* positions of ground-level gauges changed.

TABLE 2 : Comparison between rainfall amounts caught by ground-level raingauges and evapotranspiration yielded by lysimeters with vegetation covers of different aspects.

Although the results from the different lysimeters showed some scatter, most of the discrepancies could be explained by the rain trap phenomenon or by taking into account noticeable differences in the physiological vigour of the vegetation samples. On the whole, therefore, the data obtained seemed well worth the effort involved in obtaining them.

2.3 Detailed Measurements on Flow Components

2.3.1 Introduction

As was previously mentioned (see 1.1), knowledge of the flow generation processes in a drained peat area seems to be an essential factor in achieving a better understanding of the effects of drainage on peat hydrology, particularly if any attempt is made to model such behaviour mathematically. The processes which control catchment response to rainfall, have been widely studied in recent years and detailed reviews on the subject have been published by Chorley (1978), Dunne (1978) and Ward (1975).

The classical interpretation of flow generation processes has long been that put forward by Horton (1933, 1945). According to him, the surface of a permeable soil divides the rainfall falling on it into two parts. The first part consists of water which infiltrates into the soil and then reaches a stream as groundwater flow. The second part consists of overland flow which occurs when the rainfall intensity exceeds the infiltration capacity of the soil. This type of flow reaches the stream as surface runoff. Streamflow is thus envisaged by Horton as consisting of variable quantities of groundwater flow and surface runoff. Groundwater flow moves slowly through the soil and is considered to sustain streamflow during rainless periods. Overland flow moves quickly over the soil surface and is considered to be responsible for the marked increases of streamflow during flood events.

This classical concept has been challenged in recent years as a result of several detailed studies where the described type of overland flow, usually known as "Hortonian overland flow" (Chorley, 1978; Dunne, 1978), did not occur. Hewlett and Hibbert (1967), Betson (1964), Kirkby and Chorley (1967) and Dunne and Black (1970a, 1970b), have all found that infiltration is seldom a limiting factor and that overland flow occurs only from small parts of a watershed where the soil is saturated or where infiltration capacity is greatly reduced. In most cases overland flow was found to be originated mainly by direct precipitation onto saturated areas, which are essentially an expanded stream channel system. This contributing area is a dynamic system in the sense that it may vary seasonally or throughout a storm (Dunne and Black, 1970b). This type of flow is usually known as "saturation overland flow" (Pilgrim et al, 1978; Chorley, 1978) and the ideas which explain its formation are usually referred to as the "variable source area concept" (Hewlett and Hibbert, 1967; Dunne, 1978; Ward, 1975). Another kind of quick flow is originated when the infiltrating water encounters an impeding soil horizon, causing lateral subsurface flow (Dunne, 1978). This type of flow, usually known as "throughflow" or "interflow", has been found to be the dominant process in quick flow generation by Weyman (1973, 1970), Kirkby and Chorley (1967) and Whipkey (1965). Throughflow usually only occurs where there are breaks in the vertical permeability profile of the soil (Weyman, 1973).

Delayed responses of watersheds to rainfall are mainly originated by water that moves vertically to the main zone of saturation, usually known as groundwater, and then follows a curving path to the nearest stream channel (Dunne, 1978). However,Ward(1975) reported that delayed flow from steep mountain drainage basins may consist almost entirely of unsaturated lateral flow from the soil profile . The physical principles of infiltration and groundwater movement are described in a number of publications and textbooks (e.g. Childs, 1969; Rose, 1966).

Several of the outlined flow generation processes may be operative on a given watershed and it is probable that different processes or groups of processes predominate in different watersheds (Pilgrim <u>et al</u>, 1978).

According to Atkinson (1978), before measuring the rate or magnitude of different flow components it is necessary to understand what it is one is trying to measure. He also states that it is essential at least to have a good working hypothesis.

It seems reasonable to assume that, in peatlands recently drained for forestry purposes, the water that falls directly into the ditches behaves in a different way from the water that falls on the strips between the ditches and then percolates through the soil towards the nearest ditch.

As was previously mentioned (see 1.1), some authors have stated that the water that falls onto the ditches runs out of the area quickly. Several questions can be raised concerning the hydrological response of the ditch areas. Is saturation overland flow the dominant process in these areas ? Is there any difference between the behaviour of the bottom of a ditch and that of its slopes? Can the behaviour of the slopes be explained by the variable source area concept ?

It has also been shown that the saturated hydraulic conductivity decreases exponentially with depth along a peat profile (Romanov, 1968b). Ivanov, cited in Romanov (1968b), showed that the hydraulic conductivity close to the surface is often thousands of times greater than at the base of the active layer. This active layer, according to Romanov (1968b), includes the living vegetation together with the underlying layers of partially decomposed vegetation. Abrupt changes of hydraulic conductivity from unhumified to strongly humified peat layers have been described by Good _et al_ (1977) and Boelter (1972b). Boelter (1972b) showed that when the water table dropped below the more permeable surface layer, the rate of flow was greatly reduced. In the areas formed by the strips between the ditches in the present study area, a clear change from an unhumified to a strongly humified peat layer has been found (Cuttle, pers. comm.). He noticed that the average depth of the more permeable upper layer was approximately 15 cm though this was very variable and exceeded 30 cm in places. Some questions can be raised concerning the hydrological response of these strips. Is the permeability large enough, through the whole peat profile, to allow the water to percolate to the main water table ? Does saturated throughflow, as described by Weyman (1973), occur within the upper peat layer ? Is there any possibility for Hortonian overland flow to occur ?

Techniques for measuring flow processes to answer questions like these have been reviewed by Atkinson (1978), Childs (1969) and Rose (1966). After studying these reviews, and taking into account the equipment, money, and time available for such an investigation, it was decided to use a combination of 3 runoff plots and 2 nests of piezometers for this part of the research study.

2.3.2 Runoff Plots

During the first season of observations, from May to November 1979, flow processes were monitored using two runoff plots located on areas drained by 60 cm deep ditches.

To monitor flow components originated by rainfall falling on the strips between ditches and then percolating through the soil towards the nearest ditch, a covered plot, as illustrated in Plate 5, was used. A section of ditch, approximately 2.5 m long, was isolated using two small dams made of galvanized iron sheet. The sheets used were 90 cm x 60 cm and were pushed into the bottom of the ditch so that 40 cm of the sheet remained buried

Plate 5 : The covered runoff plot.

below it. A pvc pipe allows up-ditch flow to cross the runoff plot without hydrological interference. The water emerging from the ditch slopes and from the bottom of the ditch section is collected at three different levels. Two upper gutters, one at each side of the ditch, collect flow emerging from the top layer (0 - 20 cm below surface of strips). Two lower gutters collect flow emerging from the intermediate layer (20 - 40 cm below surface of strips). The ditch itself collects flow emerging from the lower layer of the slopes (40 - 60 cm below surface of the strips) and from the ditch bottom. A roof, made of black painted corrugated sheet, prevents rain from falling directly onto the studied ditch section. Similar systems to this have been used by Pilgrim et al (1978), Weyman (1973) and Whipkey (1965). According to Atkinson (1978), distortions on the flow processes to be measured are kept to a minimum when the gutters are installed in natural stream banks. This being so, realistic measurements of flow components might be expected from the apparatus described. The gutters were made of galvanized iron sheet and were inserted horizontally into the slopes of the ditch section at the required levels. The outlets of the gutters and of the plot bottom were protected by thin mesh filters. The three different flow components collected were led independently by pipe to a recording system. The connecting pipes were 8 m long and allowed water to reach the recording system by gravity. This length of the connecting pipe was used to ensure that the excavations needed to install a recording system would not interfere with the hydrology of the plot. All pipe connections were tested against leakage. The effective area of strip drained by the plot could be determined with some accuracy since it has been demonstrated that in a series of equidistant parallel ditches, with the distance between them small compared with their length, the flow net is two dimensional in the plane perpendicular to the length, and vertical planes midway between neighbouring ditches provide streamline boundaries (Childs 1972, 1969). This being so, the area contributing to the plot is defined by lateral projections of the two dams and midway lines between neighbouring ditches.

The information on flow processes obtained from the above plot was complemented by the use of an additional uncovered plot (Plate 6). This plot has the same dimensions and the same basic design as the previous one but has neither gutters nor roof. The bottom of this plot collects all the flow components emerging from the strip areas plus the water that falls directly onto the ditch section. The plot has a single outlet in its bottom which connects to a recording system. Assuming that the areas of strips drained by the two described plots have the same behaviour, flow originating from direct rainfall onto the ditch section can be computed as the difference between the integrated flow measured from the uncovered plot and the flow from the strips measured independently

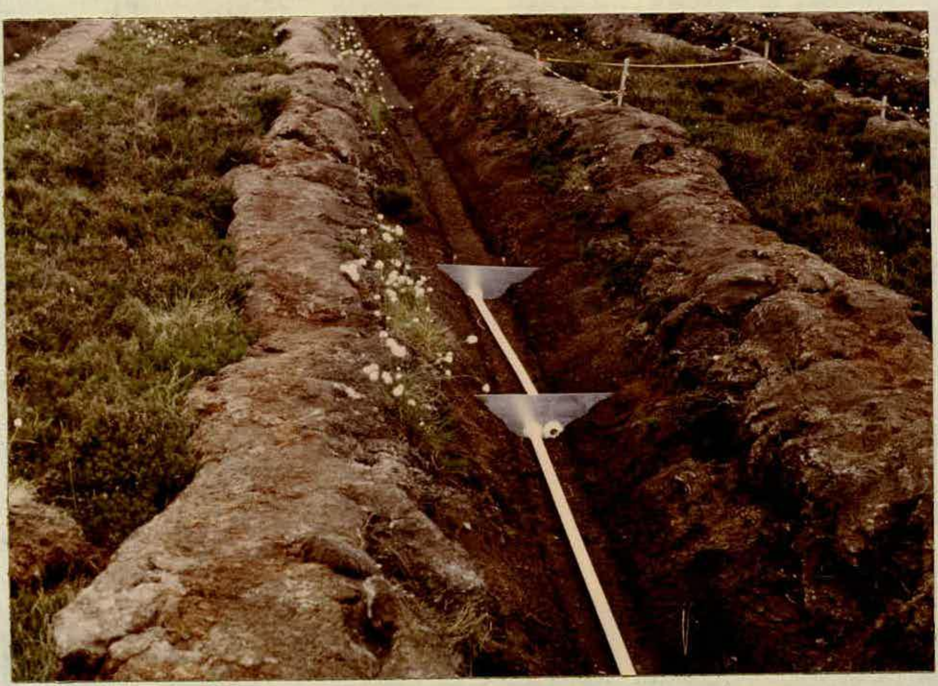


Plate 6 : The uncovered runoff plot.

by the covered plot.

Discharge rates from the two plots were monitored using siphons (Plate 7) built according to a design devised by Cuttle (1979). Constructional details of the siphons are shown in Figure 9. Gilman (1971) used siphons to record flow rates from natural pipes occurring in a small mountain catchment. Siphons were used instead of other possible alternatives, i.e. tipping-bucket gauges or stop watch and measuring cylinder (Atkinson, 1978), because some background experience was available in the use of such devices at the particular site (Cuttle, 1979). The original design devised by Cuttle had, however, to be adjusted to the requirements of the present work. The siphon size had to be determined according to the expected maximum and minimum flow rates from the plots. In particular it had to be big enough so that the time elapsed between any two successive discharges, even at the highest expected flow rate, could be monitored with some accuracy. The diameter of the siphon tube of the original design had to be increased in order to prevent continuous siphoning at high flow rates (Atkinson, 1978): the rate of discharge of the siphon has to be higher than any possible input rate. The outer chamber of the siphon was divided into a lower outer chamber, with a bigger diameter where a significant amount of water can be stored, and an upper outer chamber, with a smaller diameter to facilitate the functioning of the instrument at low input rates.

Plate 7 : The siphons used to record the flow components emerging from the covered runoff plot.

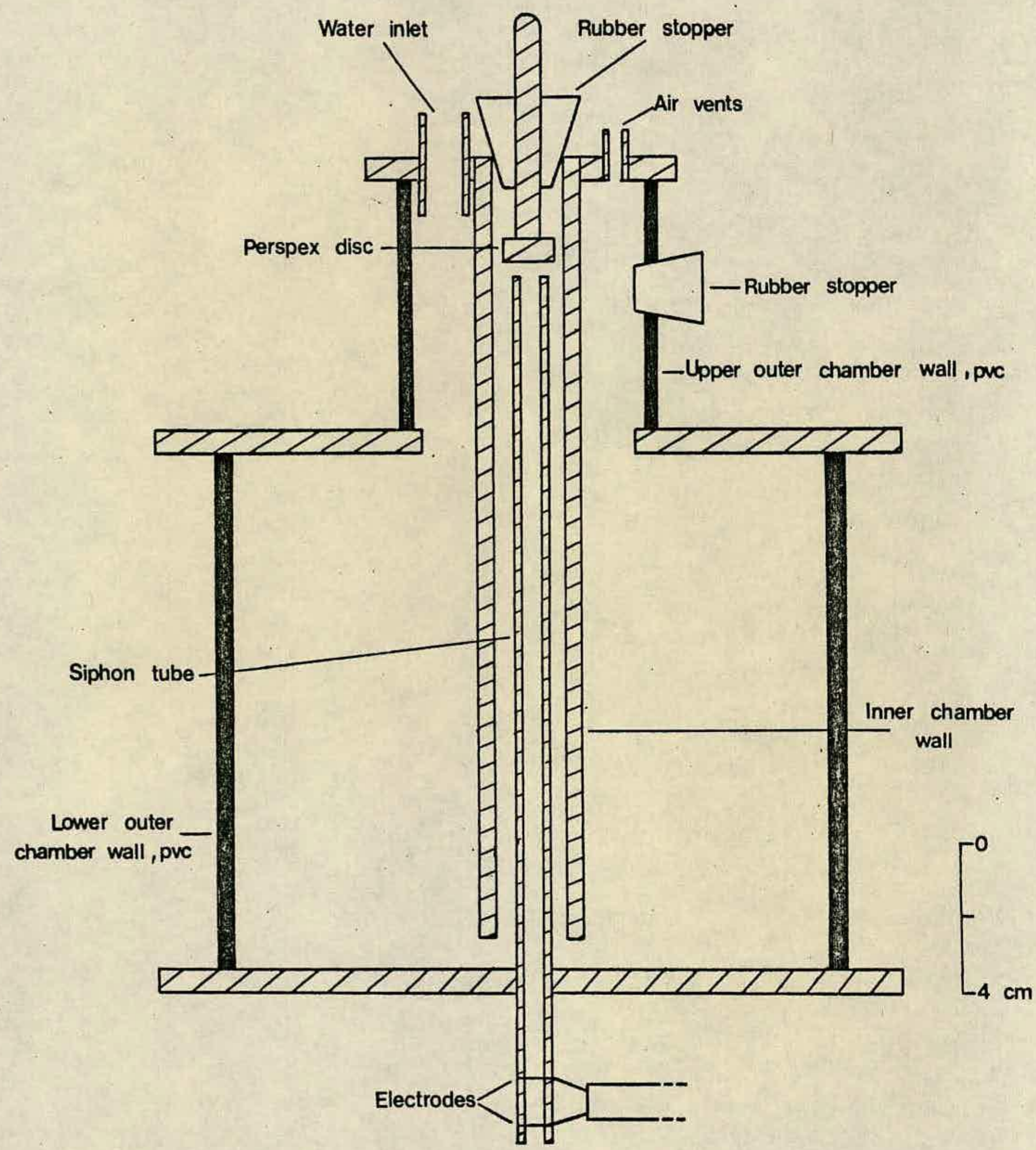


Figure 9 : Diagram showing the constructional details of the siphons.

The smaller the diameter of the upper outer chamber, the bigger the increase in head for a given input amount when the water level is near the siphon tube top and thus the better the behaviour of the instrument at low input rates. All the siphons worked very well for the whole range of observed flows.

During each discharge of the siphon, water makes a contact between two electrodes which cross the siphon tube outlet. This contact switches on an electronic circuit and the pulse originated is recorded in the already mentioned 8 channel event recorder (see 2.1.2). Each siphon is connected with an independent channel. An electronic timer, giving a pulse each five minutes, was connected with another channel of the event recorder.

Average flow rate between two successive discharges of each siphon was computed using the formula:

$$Fr = CAP/\Delta T \qquad (10)$$

in which Fr is the flow rate, CAP is the known volumetric capacity of the siphon and ΔT is the time elapsed between two successive discharges of the siphon. The total outflow from each siphon during a given period of time was computed by multiplying the volumetric capacity of the siphon by the total number of times it emptied during that period. Each siphon was calibrated before installation and after removal. The siphons used have a volumetric capacity of approximately 2.7 litres.

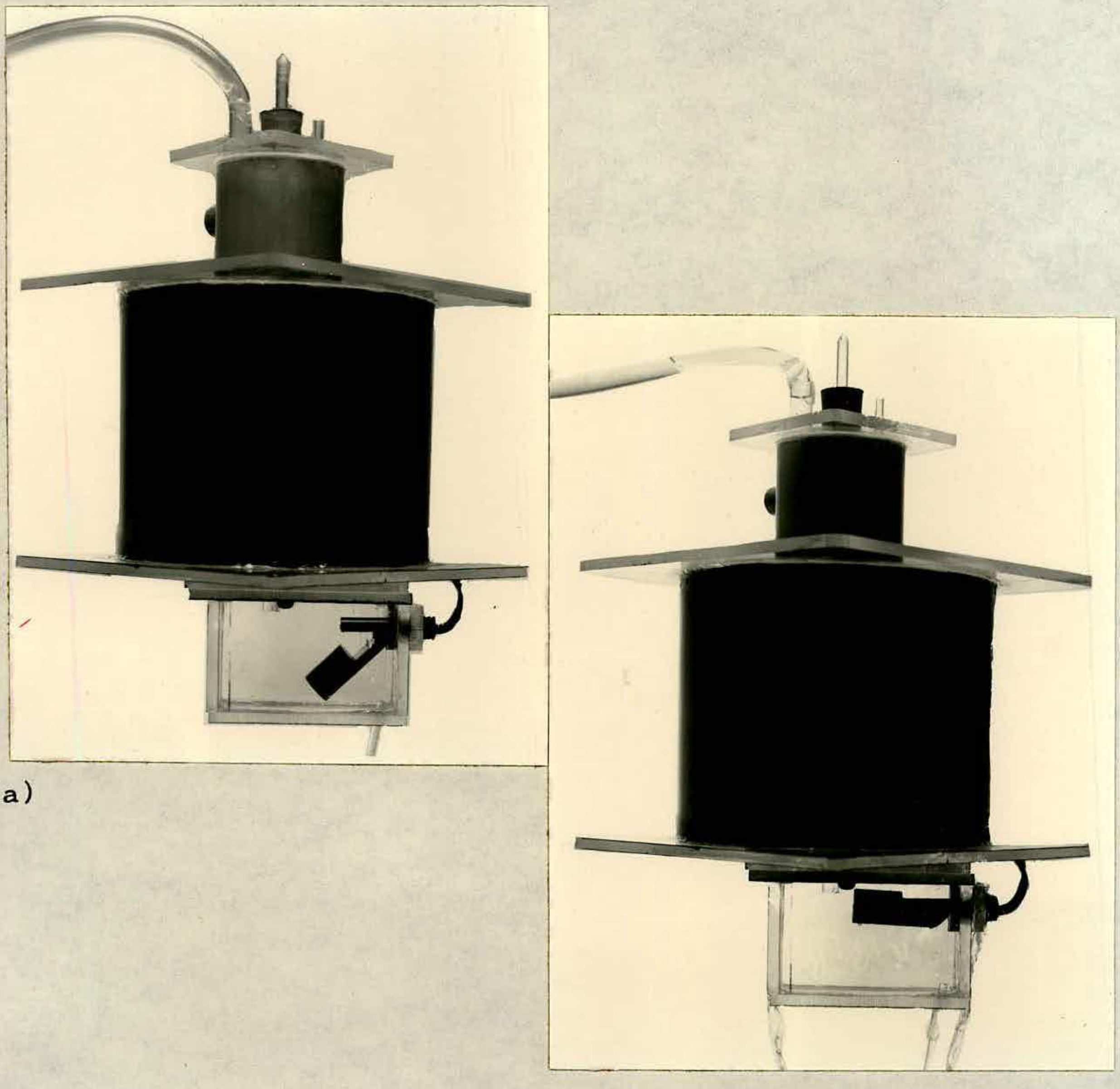
During the first season of observations, during the summer and autumn of 1979, the whole installation worked much better than had been expected. However, some instrumental shortcomings had to be solved for the following season of observations. Some problems were found with algal development inside the siphons. Small bits of this vegetation type accumulated on the siphon tube top, causing malfunctioning of the instrument. Under these circumstances and when the water level is at the siphon tube top, weak points are created on the meniscus surface and the instrument starts dripping and does not siphon. This malfunction could be easily detected by visual inspection and could be solved by cleaning the siphon tube top. At the end of the first season some joints in the siphons started to break although none of them was leaking. Also some electrodes, located at the siphon tube outlet, were showing signs of corrosion. On account of chart disengagement on the event recorder, due to excessive moisture, some periods of observations were also lost during this first period. This same problem was experienced by Mosley (1979).

To solve these problems some rearrangements were made to the apparatus. To prevent moisture interference on the recording system, the event recorder was kept sealed inside polythene bags containing silica gel. Twelve new siphons were built, with the same dimensions as the earlier ones, but with reinforced joints and a new electronic recording system. In the new siphons, each discharge was recorded by a switch-float (RS/339-730) installed in a small box located at the siphon tube outlet (Plate 8). The small perspex box containing the switch-float has an outlet in its bottom that is not big enough to drain immediately all the discharge from the siphon. When the siphon discharges, the box fills with water and thus the switch-float rises and is activated (Plate 8b). When the box is full, additional discharge from the siphon just overflows the box walls. When the siphon discharge stops, the box is emptied by the small bottom outlet and thus the switch-float falls and is switched off (Plate 8a).

To have a further check on the results of the two original plots, a new uncovered plot with the same dimensions and the same design as the first one was installed in April of 1980.

During the summer and autumn of 1980, the whole installation worked very well and no major problems were found with any of its components. Figure 10 shows a specimen of the chart from the event recorder when all the experimental network was operating.

Most previous work of this type has yielded data covering only a small number of flood events (Pilgrim et al, 1978; Weyman, 1973; Whipkey, 1965). In the present work, however, an almost continuous run of records was obtained from May until November 1980. The experiments had to be stopped during winter periods to prevent frost damage to the siphons. This long period of continuous record, allowed some computations to be made on the water balance of the plots, although this



(a)

(b)

Plate 8 : The switch-floats used to record the siphon discharges.

(a) Siphon not discharging: switch-float on an "off" position.

(b) Siphon discharging: switch-float on an "on" position.

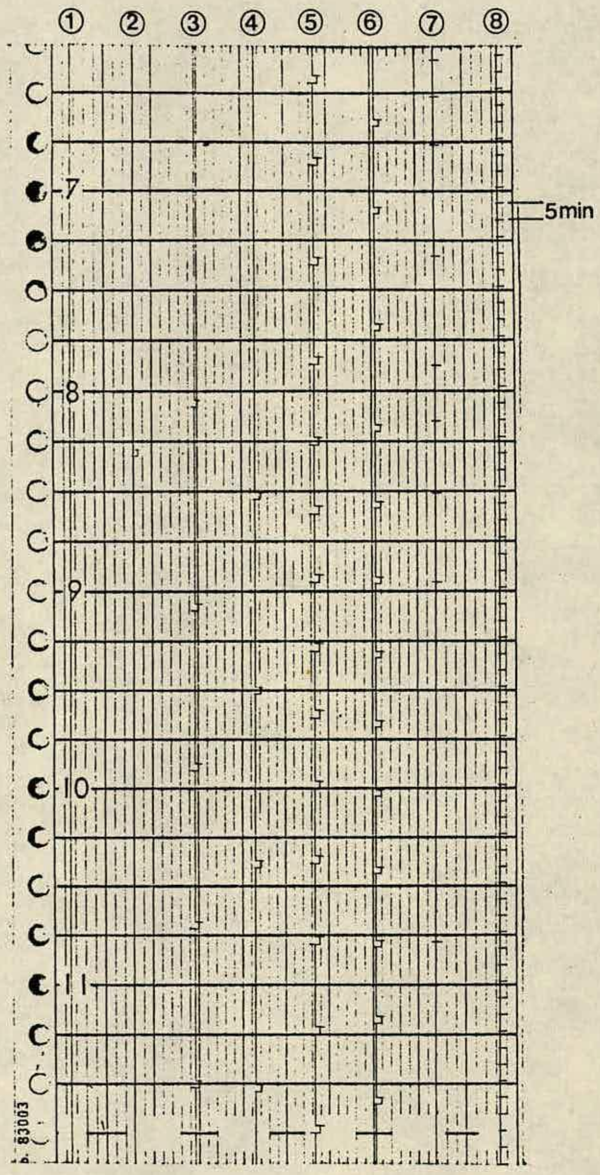


Figure 10 : A copy of the event recorder chart for October 22, 1980.
Numbers inside circles indicate the channel number. Channel 1 was allocated to manual time checking, channels 5 and 6 to the siphons of the uncovered runoff plots, channels 2,3 and 4 to the siphons of the covered runoff plot, channel 7 to rainfall and channel 8 to time.

was not an initial purpose of this particular experiment. Water balance calculations for the plots were used as an additional method to check evapotranspiration results yielded by other sources (see 2.2.1). For water balance calculations, flow volumes had to be converted into equivalent millimeters of runoff. This was no problem since, as has already been described, areas drained by the plots could be defined according to theoretical principles (Childs, 1972, 1969). Data from the covered plot allowed independent estimates of evapotranspiration for areas constituted by strips and data from the uncovered plots allowed the computation of evapotranspiration estimates for areas integrating strips and ditches. Average dimensions of the contributing area width for an uncovered plot are given in Figure 11. The contributing area length, as was previously mentioned, equals the distance between dams, i.e. 2.5 m. Contributing area width for the covered plot was obtained by subtracting the roof width, which equals the ditch width, from the total contributing area of an uncovered plot.

2.3.3 Piezometers

As was mentioned earlier two series of piezometers had been monitored at the site by Dr. S. Cuttle since March, 1978. Each series of piezometers monitors water pressure at different depths along a cross section of a strip between ditches. Each series consists of three rows of piezometers (Figure 12): one row 80 cm deep,

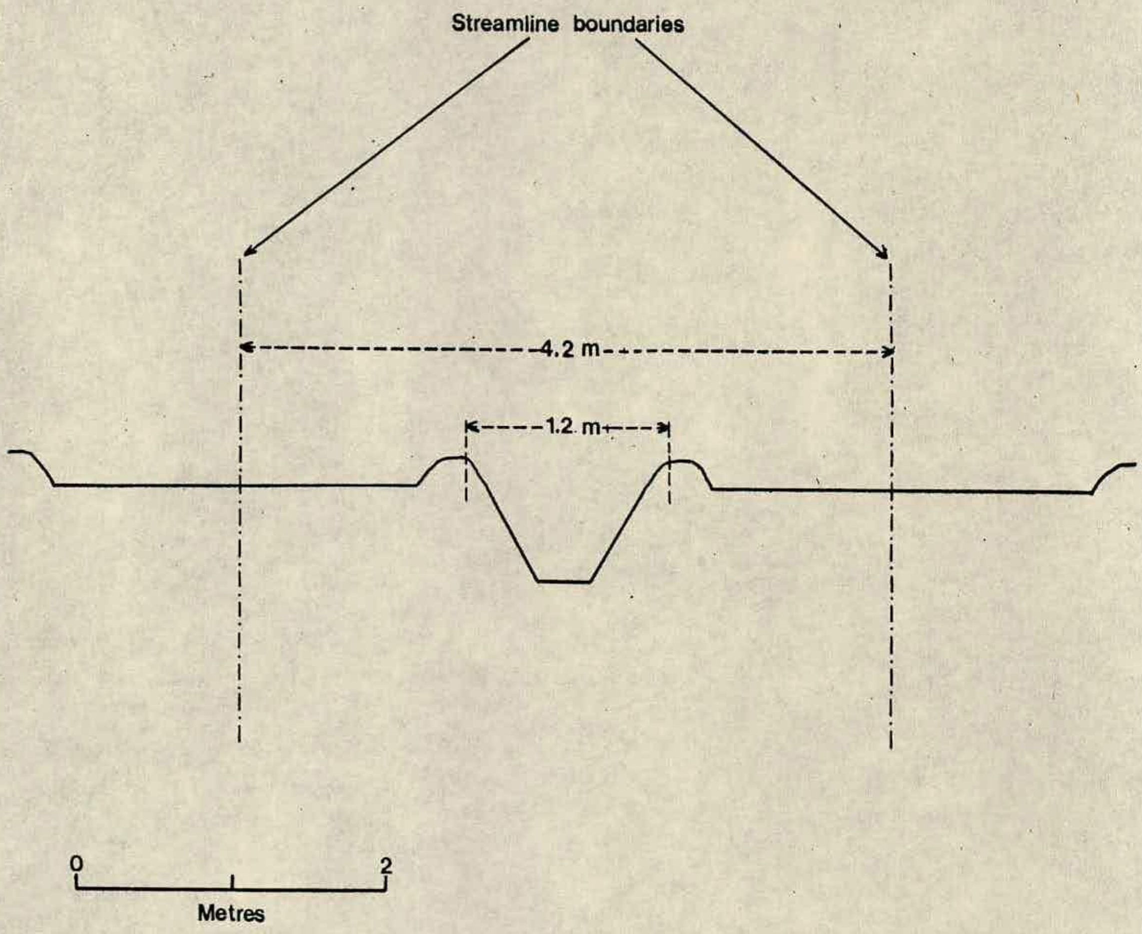


Figure 11 : Diagram showing the width of the contributing area to one uncovered runoff plot.

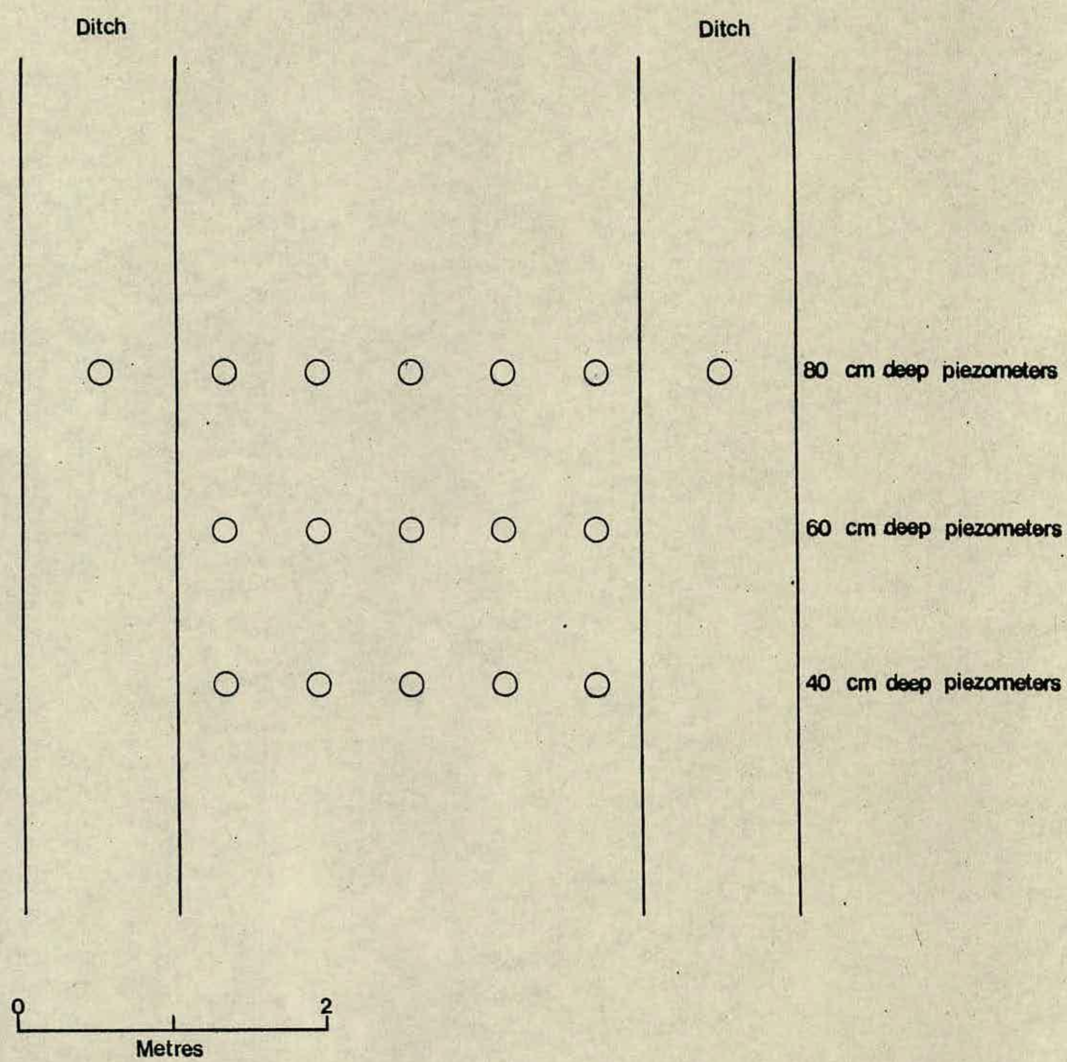


Figure 12 : Plan view showing a nest of piezometers along a cross section of a strip.

one row 60 cm deep and one row 40 cm deep. Both series are located on strips between 60 cm deep ditches. The piezometers were made of upvc pipe of a diameter of 22 mm. Readings of water levels inside the piezometer tubes had been taken weekly.

Available data were analysed by the author. The hydraulic head at the bottom of each piezometer tube was computed according to Figure 13 (Ward, 1975; Donald, Donald and Wigham, 1973; Rose, 1966) by the formula:

$$H = h + z \tag{11}$$

in which H is the hydraulic head also known as hydraulic potential (cm), h is the submergence potential also known as piezometric head (cm), and z is the gravitational potential (cm), i.e. the height of the piezometer bottom above a specified datum level. In the present case the datum level used was a horizontal line 80 cm below ground surface. As the inflow of water into the ditches is conducted away quickly, it can be assumed that the submergence potential is zero at the ditch bottoms (Rose, 1966) and thus its hydraulic potential will be equal to the gravitational potential. Equipotential lines, i.e. lines of equal hydraulic head, can be drawn by interpolations from the data supplied by the piezometer nests (Reeve and Jensen, 1949). Steamlines define the direction of water movement and are perpendicular to the equipotential lines (Donald, Donald and Wigham, 1973; Boelter, 1972b). Boelter (1972b) and Neuman and Dasberg (1977), studied saturated water move-

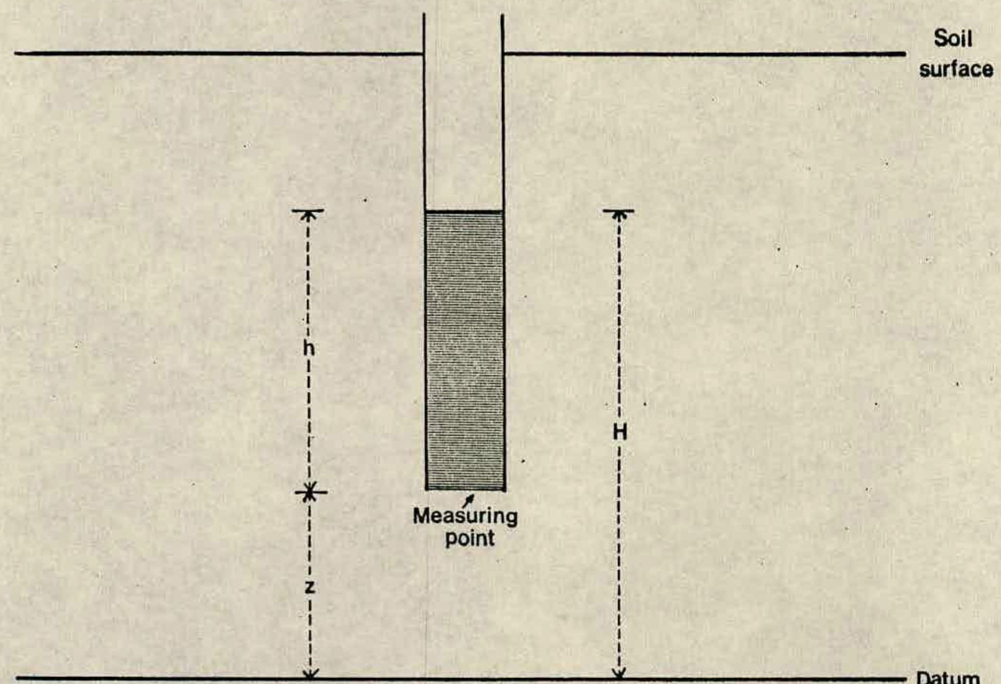


Figure 13 : Diagram illustrating the computation of hydraulic head from piezometer readings.

ment within peat areas using equipotential lines drawn from data supplied by piezometer nests. In the present work a similar data analysis was undertaken. Equipotential lines were drawn on a two dimensional basis as if the three piezometer rows of each series were located on the same cross plane.

Saturated flow within the soil is usually governed by the Darcy's law (Ward, 1975; Donald, Donald and Wigham, 1973) which can be written as :

$$V = k \times i \tag{12}$$

in which V is the velocity of flow, k is the saturated hydraulic conductivity and i is the hydraulic head gradient. Saturated hydraulic conductivity was measured at the site by Dr. S. Cuttle. However, Ingram et al (1974) and Rycroft et al (1975a, 1975b) argued that, within humified peat layers, water does not move according to Darcy's law.

Quantity of water flowing per unit time through a cross sectional area, A, is given by the equation (Reeve and Jensen, 1949):

$$Q = V \times A \tag{13}$$

in which Q is the flow rate, V is the velocity and A the cross sectional area.

Rate of water movement into the ditches was calculated from the equipotential lines using the method described by Reeve and Jensen (1949). In this method equation (12) and (13) are solved using an average hydraulic head gradient around the ditch, determined graphically from equipotential lines. However, the piezometer network was not dense enough to calculate with accuracy the parameter A of equation (13). This parameter defines the periphery of the bottom of the ditch from which saturated flow emerges.

2.3.4 Other Measurements

As was mentioned in the previous sections all the experimental network on flow processes, i.e. the flow measuring plots and the piezometer nests, was located on areas drained by 60 cm deep ditches. Although it was not possible to carry out similar detailed work on areas drained by other types of ditches, it was thought necessary to have some information about the influence of ditch type on outflow. For this purpose outflow rates from two 90 cm deep ditches and two 60 cm deep ditches were measured during each visit to the site, from July until November of 1980, using a stop watch and a measuring cylinder. To facilitate flow rate measurements, a small dam with an outlet pipe was installed at the exit of each monitored ditch.

To compare flow rates from the different ditches, the contributing area to each ditch had to be known. Due to the domed shape of the site only part of the total length of each ditch contributed to its monitored exit. Milk was poured into different sections of each ditch to locate the upper boundary of its contributing length.

Contributing area width was measured assuming that midway lines between neighbouring ditches provide streamline boundaries (see 2.3.2).

PART 3

RESULTS

3.1 Introduction

It is evident from the work described in Part 2 of this thesis that the research project at Leadburn yielded a great quantity of data on many different hydrological variables. It seems important, therefore, at this stage to give a brief resumé of the data available as well as to make a few comments on how the results will be presented.

Figure 14 shows the location at the site of the different experimental instruments. Figure 15 shows the periods of time during which the different hydrological instruments were monitored continuously or intermittently. In Figure 15 weekly records are considered as continuous.

Weekly as well as continuous records of rainfall are available for a period of approximately three and a half years, beginning almost since drainage had been carried out.

Continuous runoff records are also available for the same period. Outflow rates from 60 cm and 90 cm deep ditches were measured independently on a weekly basis during the last 5 months of the study period. Data from the runoff plots are available for the autumns of 1979 and 1980 and for the spring and summer of 1980. The longest continuous run of reliable records from this experiment lasted for a period of 5 months, from the 29th of April to the 30th of September 1980. During the rest of the period, data on flow components are only

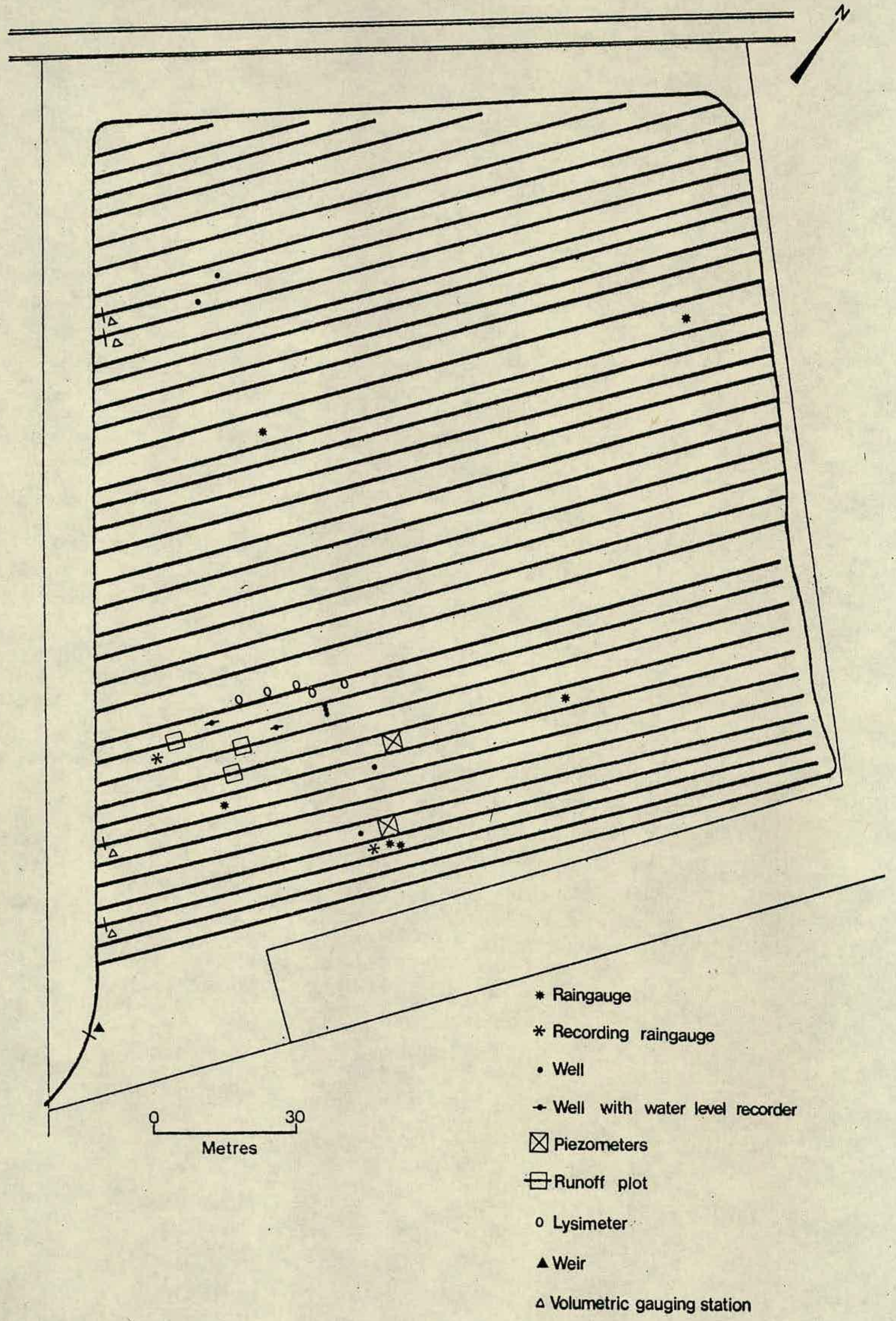


Figure 14 : Map of the experimental area showing the location of all the hydrological instruments used in this study.

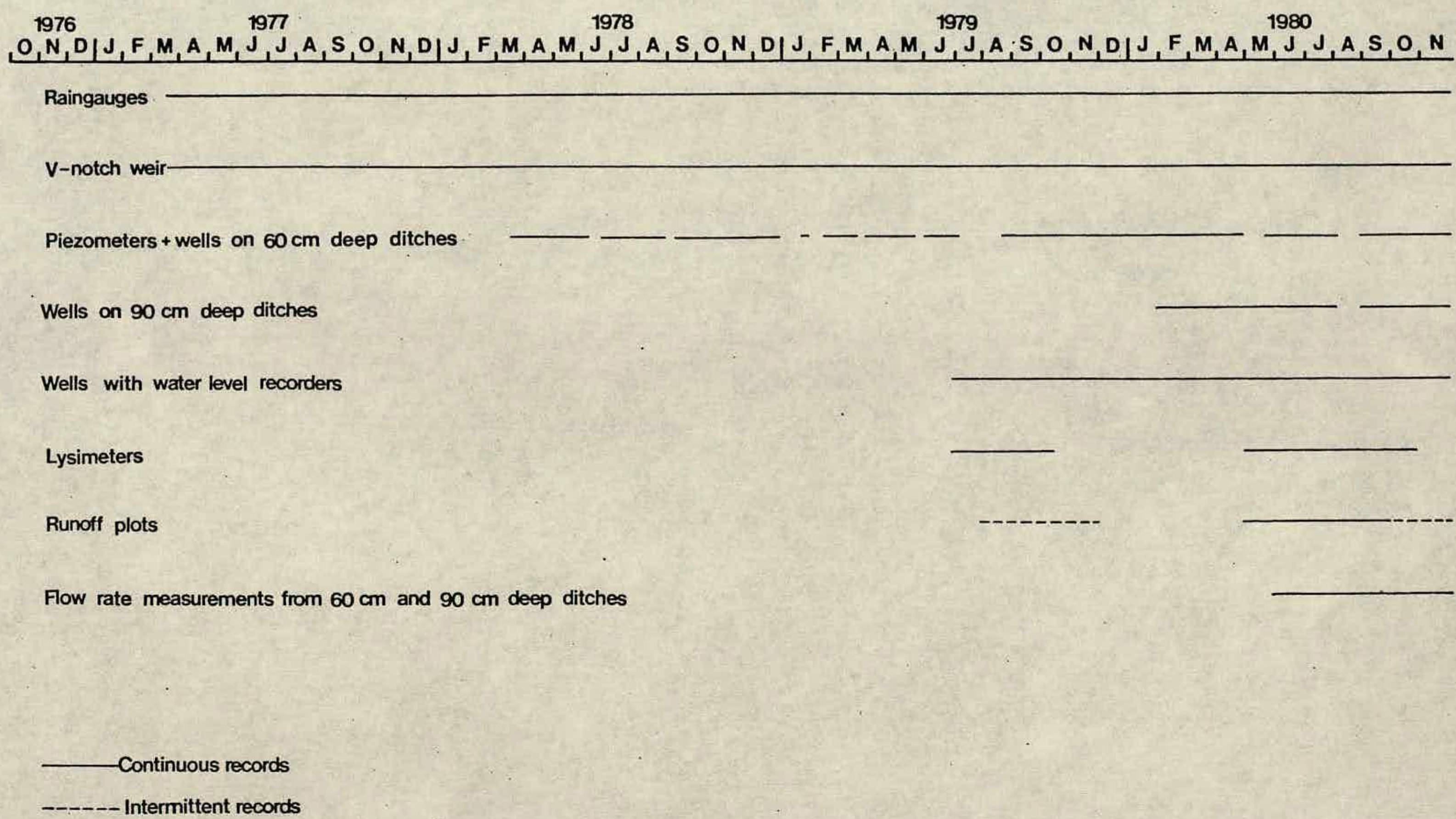


Figure 15 : Diagram showing the periods during which the different hydrological instruments were monitored.

reliable for intermittent and shorter intervals.

Water table levels were measured weekly on strips between 60 cm deep ditches for a period of approximately two and a half years. This monitoring began 1 year later than that of rainfall and runoff and in addition data are not available for some short winter and summer periods. Water table level was also measured weekly on the centre of strips between 90 cm deep ditches during the last 10 months of the study period. Continuous records of water table levels on strips between 60 cm deep ditches are also available for the last 16 months of the period. Weekly data from two piezometer nests are available for a period of two and a half years, coinciding with the period of weekly water table records from areas drained by 60 cm deep ditches.

Evapotranspiration was measured weekly from lysimeters for the growing seasons of 1979 and 1980.

This brief description clearly indicates that during some periods there is overlapping information from a large number of different experimental sources. The most intensive data analysis will obviously fall upon such periods.

Dealing systematically with such a profusion of results is by no means an easy task. After some consideration it was felt that their presentation would best be achieved by organizing this part of the thesis according to the general aims indicated in the Introduction (see 1.1). These are: the characterization of the water balance of the study area, the identification and quantification of the dominant runoff processes, the study of the specific relationship between flow rates and water table depth and the mathematical modelling of the response of the area to rainfall. Accordingly the results part of this thesis is divided into four main sections concerning the four topics listed above. In each section, data analysis relevant to its specific subject is discussed and presented.

3.2 Water Balance

3.2.1 Water Balance for the Whole Area

As was described earlier the main components of the water balance of the experimental site had been monitored almost since drainage had been carried out. In Appendix 2 detailed weekly information is presented on rainfall, water table and runoff measured at the V-notch weir. Before presenting any detailed analysis of the results it must be kept in mind that runoff data during frost affected periods are not reliable (see 2.1.4). This is clearly shown by water balance calculations for the three winter periods covered by these records (Table 3). Actual evapotranspiration was calculated using equation (3) as the simple difference between rainfall and runoff, thus assuming water storage variations as zero (see 2.2.1). Table 3 shows that the water balance method yields negative estimates of actual evapotranspiration for the second and third of these periods. In both of these periods water table depth, on the centre of strips between 60 cm deep ditches, had similar values at the beginning and end of each period (27.8 cm and 27.3 cm for the second period and 38.7 cm and 28.2 cm for the third period). Thus the big negative estimates of actual evapotranspiration cannot be explained by having neglected possible water storage variations in the calculations. Possible catch deficits by the raingauges are unlikely to exceed

Year	Period (Frost affected)	Rain (mm)	Runoff (mm)	Rain-Runoff (mm)	Potential Evapotranspiration (mm)	
					Bush	Penicuik
1	22/11/77 27/ 3/78	280	267	13	28	42
2	5/12/78 2/ 4/79	332	398	-66	37	48
3	13/11/79 31/ 3/80	406	510	-104	32	42

TABLE 3 : Water balance calculations for winter periods.

10 % (see 2.1.2), so the maximum possible underestimation of the true rainfall is unlikely to exceed 36 mm for the second winter period and 44 mm for the third one. These possible errors are not big enough to explain entirely the negative evapotranspiration estimates shown in Table 3. It seems then that the main explanation for this fact is the overestimation of runoff amounts due to the ice effects described earlier (see 2.1.4). Table 3 also shows that in this part of Scotland, potential evapotranspiration computed by the Penman formula, over the winter periods is very small, amounting to only 8 - 15 % of the total rainfall measured. This being so, it seems reasonable to assume that during such periods total runoff equals total rainfall. Even if actual evapotranspiration equals potential evapotranspiration the maximum errors that such an approximation will yield on the new assumed runoff values would be of approximately 15 %. This assumption is supported by rainfall and runoff data for some frost free winter periods in which ice effects are not present (Table 4). Table 4 shows that during the three analysed periods, total runoff is fairly close to the corresponding total amount of rainfall. Due to the errors in winter runoff data, in any further data analysis of frost affected periods it will be assumed that runoff equals rainfall. This will certainly yield more accurate results than if recorded runoff data were used directly.

The obvious approach to a first estimate for the

Period	Dates	Rainfall (mm)	Runoff (mm)
1	1/11/77 7/11/77	41	37
	8/11/77 14/11/77	28	28
	15/11/77 21/11/77	14	12
	TOTAL	83	77
2	7/11/78 13/11/78	37	14
	14/11/78 20/11/78	54	65
	21/11/78 27/11/78	11	10
	28/11/78 4/12/78	9	6
	TOTAL	111	95
3	7/10/80 13/10/80	1	5
	14/10/80 20/10/80	48	37
	21/10/80 27/10/80	38	46
	28/10/80 3/11/80	2	6
	4/11/80 10/11/80	22	11
	TOTAL	111	105

TABLE 4 : Comparison between rainfall and runoff during winter periods free of snow and ice.

actual evapotranspiration from the experimental site, which integrates ditches and strips (see 2.2.1), is given by the application of the water balance method using available rainfall and runoff data. Due to the inaccuracies of the winter runoff data, computations were done dividing each year of record into two seasons: a frost free season and a frost affected season. Table 5 shows the seasonal water balance for three years covered by these records. This indicates that annual rainfall and annual runoff have fairly consistent values for the three years of record. Annual rainfall varied from 967 to 876 mm and annual runoff from 596 to 690 mm. As a result, water balance calculations yielded fairly similar annual evapotranspiration estimates for the different years.

The following analysis of data of Table 5 will be concerned with the results for the frost free seasons of each year from which more reliable water balance calculations can be expected. In actual evapotranspiration calculations for these frost free seasons, variations in storage were again assumed to be negligible, which seems a reasonable approximation since the beginning and end of each of these periods are respectively at the beginning of spring and end of autumn which are both wet periods and thus should present similar water table levels. It can be seen that calculated actual evapotranspiration for the frost free seasons is 16 - 29 % lower than potential evapotranspiration from Bush and 25 - 42 % lower than potential evapotranspiration from Penicuik. All potential evapotrans-

Year	Period		Rainfall (mm)	Runoff (mm)	Actual Evapotranspiration (Rainfall-Runoff) (mm)	Potential Evapotranspiration (mm)	
						Bush	Penicuik
1	Frost Free	16/ 3/77 21/11/77	687	410	277	388	474
	Frost Affected*	22/11/77 27/3/78	280	280*	0*	28	42
	TOTAL		967	690*	277*	416	516
2	Frost Free	28/ 3/78 4/12/78	612	308	304	361	404
	Frost Affected*	5/12/78 2/ 4/79	332	332*	0*	37	48
	TOTAL		944	640*	304*	398	452
3	Frost Free	3/4/79 12/11/79	470	190	280	382	397
	Frost Affected*	13/11/79 31/3/80	406	406*	0*	32	42
	TOTAL		876	596*	280*	414	439

* values corrected for frost affected periods

TABLE 5 : Seasonal water balance calculations for the whole area. Each year was divided into two seasons: a frost affected season and a frost free season.

piration values were computed by the Penman formula. Pan evaporation data from Bush will not be used hereafter as it was found that, particularly during 1980, the readings of the water levels inside the pan were not being taken properly.

The results indicate systematically that actual evapotranspiration from the whole area is lower than potential evapotranspiration estimated by the Penman formula. This general conclusion should be expected as it is known that on a short-term basis evapotranspiration from bogs is usually reduced after drainage (see 1.1).

To try to explain such evapotranspiration reductions, it must be kept in mind that drainage for forestry purposes originates two very different types of ground surface: the vegetated areas of the strips which remain between the ditches and the sheltered and almost bare areas of the ditches (see 2.2.1). These two component parts of the whole area probably have different evapotranspiration losses and thus separate water balance calculations for the ditches and strips will certainly complement the already shown results on the general water balance of the whole area. These separate water balance calculations are presented in the next section.

3.2.2 Separate Water Balances for Strips between Ditches and Ditches

Actual evapotranspiration from the strips and from areas integrating ditches and strips can be separately calculated by solving the water balance equation for the runoff plots (see 2.3.2). Actual evapotranspiration from the strips can be calculated for the covered runoff plot and actual evapotranspiration from areas integrating strips and ditches can be calculated for the two uncovered plots. If actual evapotranspiration from strips and from areas integrating ditches and strips is known, equation (5) can be used to estimate the actual evaporation from the ditches (see 2.2.1). To apply equation (5) to the runoff plots, it must be assumed that the actual evapotranspiration from the areas of strips contributing to the uncovered plots equals the actual evapotranspiration from strips as measured at the covered plot. To perform the calculations, the area of ditches, the area of strips and the total area, integrating ditches and strips, must be known. The values of these parameters for the runoff plots are respectively of 3.0 m^2, 7.5 m^2 and 10.5 m^2 (see 2.3.2). The calculations were performed for a period of five months, from the beginning of May to the end of September 1980, during which the runoff plots gave a continuous run of data (Table 6). Water balance calculations for the period were performed assuming water storage variations to be negligible. This assumption seems reasonable as water table depths were fairly similar at the beginning and end of the period, being 53.3 and 42.3 cm respectively. The results in Table 6 show that actual evapotranspiration from areas integrating ditches and strips again falls systematically below potential

Period : 29th April, 1980 - 30th September, 1980

		Rain (mm)	Flow (mm)	Actual Evapotranspiration (mm)	Potential evapotranspiration (mm)	
					Bush	Penicuik
Ditches + Strips	Uncov. Plot 1		99.8	279.6		
	Uncov. Plot 2		104.1	275.3		
	Mean		101.9	277.5 (1)		
Strips	Covered Plot	379.4	58.7	320.7 (2)	302.1	316.6
Ditches			-	169.5*		

* Computed from (1) and (2) by equation (5)

TABLE 6 : Separate water balances for ditches, strips between ditches and areas integrating ditches and strips calculated from runoff plot data.

evapotranspiration. This confirms the results obtained for the water balance of the whole area. During the five month period actual evapotranspiration from areas integrating ditches and strips was 7 - 9 % lower than the potential evapotranspiration calculated for Bush and 12 - 13 % lower than potential evapotranspiration for Penicuik. Actual evapotranspiration from the strips, however, had a value close to the Penman potential evapotranspiration estimates, being only 6 % and 1 % higher than potential evapotranspiration from Bush and Penicuik respectively. Average actual evaporation from the ditch sections of the plots had a significantly lower value than potential evapotranspiration estimates, being respectively 44 % and 46 % less than potential evapotranspiration from Bush and Penicuik. It would seem, therefore, that it is the very low values of evaporation from the ditches when integrated with the potential values of the evapotranspiration from the strips that result in an average evapotranspiration for the whole site that is lower than the potential evapotranspiration.

It is now important to see whether these preliminary results from the runoff plots can be generalized to the whole area. The first obvious approach to this is to see whether, during the same 5 month period, the water balance calculations for the whole area yield similar results to those derived from the runoff plots for areas integrating ditches and strips. If the relative proportions between the areas occupied by ditches and strips are similar both for the two uncovered plots and for the whole area, water balance calculations from these different sources should yield similar results. The percentages of area occupied by ditches and strips are 30 % and 70 % respectively for the whole area and 28.6 % and 71.4 % for the uncovered runoff plots. During the 5 month period in question total runoff measured at the experimental area outlet amounted to 117.7 mm. Thus, actual evapotranspiration from the whole area has an estimated value of 261.7 mm if computed as the simple difference between rainfall and runoff. This new evapotranspiration estimate has, as should be expected, a very close value to the previous estimates of evapotranspiration from areas integrating ditches and strips shown in Table 6. The percentage deviation between evapotranspiration from the whole area and the average evapotranspiration from the two uncovered plots is only - 6 %. This good agreement between independent estimates of evapotranspiration indicates that the water balance calculations both for the whole area and for the runoff plots are probably correct.

Data from the localized experiment carried out at the runoff plots can also be used to derive a general method to estimate separately the total flow originated on the strip component and on the ditch component of the experimental site. This method can then be used to undertake separate water balance calculations for the two component parts of the whole area.

As was mentioned earlier (see 2.3.2), the covered plot collects flow emerging solely from its contributing area of strips, and each of the two uncovered plots collect this same flow component plus the flow which is produced by rain falling directly onto the isolated ditch section. For a given period of time, flow derived from rain falling directly into the isolated ditch section of each uncovered plot, can be calculated as the simple difference between the total flow measured at the uncovered and covered plots (see 2.3.2). Following this line of reasoning a number of flood events, recorded at the runoff plots, were analysed. Total flow for each event was computed as the average of the flow collected from the two uncovered plots. Actual ditch flow for each event was estimated as the difference between the total flow and the flow measured at the covered plot. Actual ditch flow was then compared with the flow that would be originated by direct rainfall into the ditch sections if they were working as impermeable areas. This impermeable ditch flow can be computed by the formula:

$$FIMD = AD \times P \qquad (14)$$

in which FIMD is the impermeable ditch flow (litres), AD is the ditch area (m^2) and P is the rainfall (mm). The value of AD for the uncovered plots is $1.2 \times 2.5 = 3.0\ m^2$ (see 2.3.2). Equation (14), when applied to the uncovered runoff plots, can then be written as:

$$FIMD = 3.0 \times P \ . \qquad (15)$$

The flood events analysed had variable durations ranging from one to three days. Detailed data for each event and its analysis are presented in Appendix 3. Figure 16 summarizes these data. In Figure 16 total flow and actual ditch flow for each event were plotted against the corresponding rainfall amount. The straight line represents equation (15) which defines the behaviour of the ditch sections of the plots as if they were impermeable. Figure 16 shows that:

1. If the total runoff for a flood event falls below the straight line, then actual ditch flow is smaller than impermeable ditch flow and equals total flow. This means that the measured flow from the covered plot was zero.
2. If the total runoff for a flood event falls above the straight line, then actual ditch flow is to all intent equal to the impermeable ditch flow.

These conclusions can also be expressed in the following way:

1. In fairly dry situations, hydrograph rises are due entirely to rain falling directly into the ditches and no flow from the strips is observed.
2. In wet periods the ditches work as impermeable areas and there is a significant contribution of flow from the strips.

This broad interpretation of the results fits well with most of the analysed flood events. However, some exceptions can be noticed in Figure 16. In the event identified

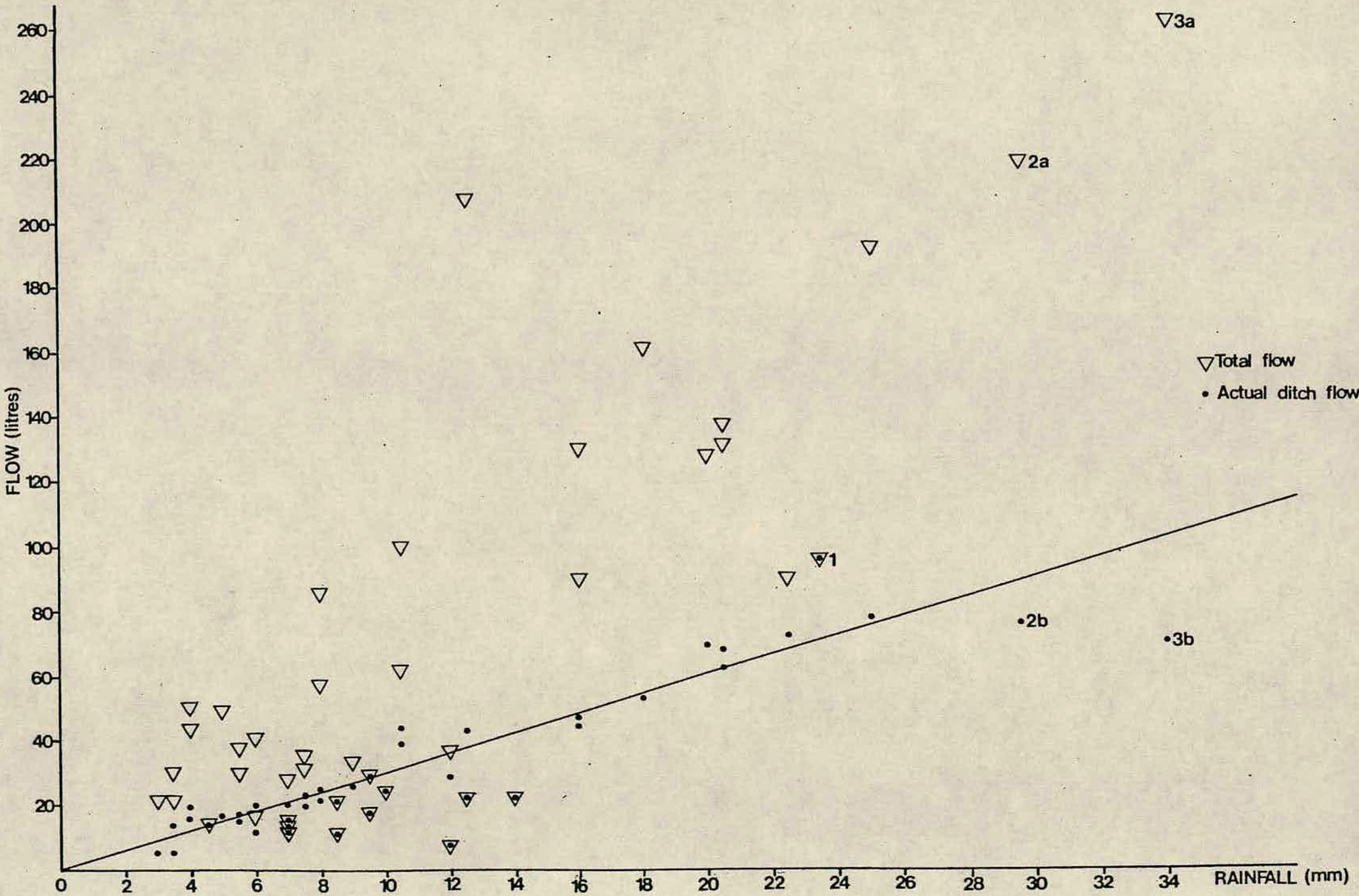


Figure 16 : Diagram showing the plotting of total flow and actual ditch flow against rainfall for several events recorded at the runoff plots.

with the number 1, total flow was bigger than impermeable ditch flow and yet no flow was measured in the covered plot. On the other hand, for the two heaviest storms (events identified with numbers 2 and 3 in Figure 16) actual ditch flow was significantly lower than impermeable ditch flow. These discrepancies can be explained by two different reasons. Firstly, during heavy storms, flow rates entering the siphon are very high and this increases the length of time during which it is discharging. During these periods some water enters and comes out of the siphon without being recorded. If, in these situations, total flow is computed by multiplying the number of siphon discharges by its volumetric capacity, important underestimations of total flow can be expected. It is important to notice that this problem is particularly important in the uncovered runoff plots from which flow rates are much higher. However, this error does not influence the accuracy of flow rate measurements between any two successive siphon discharges. Secondly, and as will be explained later, interflow emerges from the top peat layers of the strips during heavy storms. For this type of flow the assumption that midway lines between neighbouring ditches provide streamline boundaries seems not to hold anymore. This being so, different amounts of interflow are probably emerging at each of the three plots. The inaccuracies observed in Figure 16 for the two heaviest storms, are thus a direct consequence of shortcomings in the experimental design during such periods.

In spite of the exceptions noted above, the conclusions drawn are thought to be attractive enough, both by their simplicity and by their consistency for most of the events, to be applied to the V-notch runoff data to derive separate flow estimates for the strip and ditch components of the whole area. Such extrapolation implies that areas drained by the 90 cm deep and the wide 60 cm deep ditches behave in a similar way to those drained by 60 cm deep ditches from which the conclusions were drawn.

Impermeable ditch flow for the whole area can be calculated using equation (14). In this case AD was estimated as 30 % of the total area, i.e. 0.753 ha. Equation (14) can then be written as:

$$FIMD = 7530 \times P \quad (16)$$

The separate flow components for the ditches and for the strips were computed for the whole experimental site in the following way:

1. If total flow, measured at the V-notch, was bigger than impermeable ditch flow, computed from equation (16), then:

$$FD = FIMD \quad (17)$$

and

$$FID = FT - FD \quad (18)$$

where FD is the actual ditch flow (litres), FID is the actual flow from strips (litres), and FT is the total flow (litres).

2. If total flow was smaller than impermeable ditch flow, then:

$$FD = FT \quad (19)$$

and

$$FID = 0.0 \, . \quad (20)$$

To express FD, FID and FT in equivalent millimetres, they were divided by their respective contributing areas, i.e. the area of ditches (AD), the area of strips (AID) and the total area (AT). In the experimental site AD = 0.753 ha, AID = 1.757 ha and AT = 2.51 ha. It can be seen that for any period of time:

$$FT = \frac{FID \times AID + FD \times AD}{AT} \quad (21)$$

when all flows are expressed in equivalent millimetres.

Runoff data collected at the V-notch weir were analysed in this way on a weekly basis and separate estimates of flow from ditches and from strips were obtained. A specific computer program was produced to perform the calculations. Separate weekly estimates of flow from ditches and from strips are presented, together with total flow and areal rainfall, in Appendix 4. These flow estimates allowed the water balance method to be used to derive separate estimates of evapotranspiration from the strips and evaporation from the ditches. It is however important to recognize that the results yielded by this method are liable to some errors. For instance during an hypothetical period of no rain but with some flow recorded at the V-notch, the method will assign all the measured flow as flow from the strips. However the actual flow which emerges from the strips is certainly slightly higher than the flow measured at the V-notch as some evaporation will also occur during its journey down the ditches towards the site outlet. Under these circumstances, evaporation taking place at the ditch bottoms is assumed by the method to occur from the strips. Thus evaporation from the ditches will tend to be underestimated and evapotranspiration from the strips overestimated. On the other hand, during wetting up situations after a dry period some of the water falling into the ditches moves laterally towards the strips thus contributing to their storage. This is clearly shown by the hydraulic head data yielded by the piezometers, particularly for the piezometer series II (Figure 17). In Figure 17, hydraulic head data were only derived from the deeper piezometers (80 cm deep) as the shallower piezometers were dry during that specific period. This water that moves into the strips from the ditches is in fact ditch flow that does not reach the V-notch. Under these circumstances the method will tend to overestimate evaporation from ditches and underestimate evapotranspiration from strips.

With the available information it is difficult to assess the relative importance of these errors on the results obtained using this method. However, to test the possible reliability of the method it was initially applied to the 5 month period during which similar data were also available from the runoff plots. Table 7 shows the separate water balance calculations for the

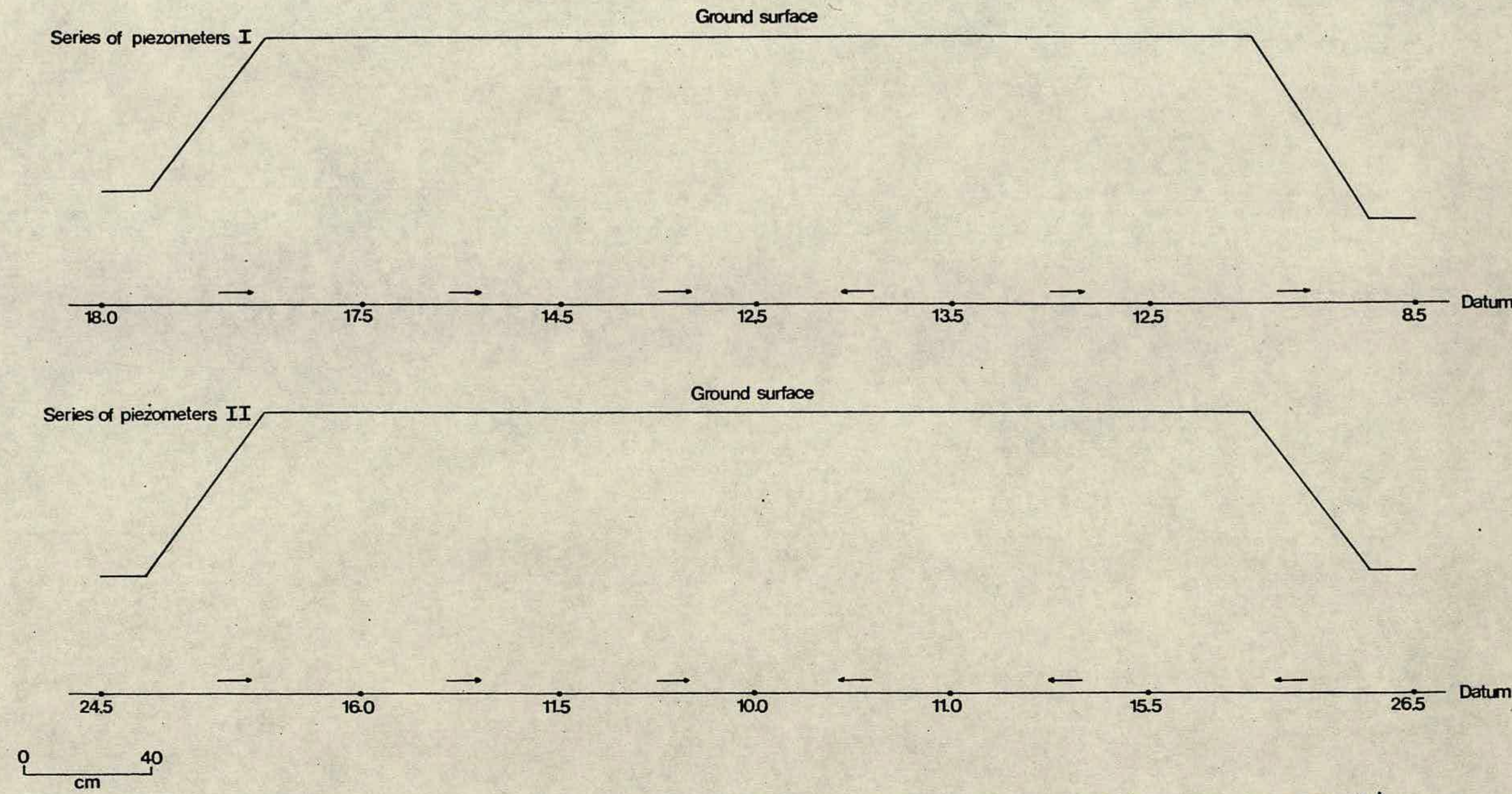


Figure 17: Diagram showing hydraulic head data and direction of flow on August 14, 1979. This graph typifies a wetting up situation preceded by a long dry period.

PERIOD: 29th April 1980 - 30th September 1980

	Rain (mm)	Flow (mm)	Actual Evapotranspiration (mm)	Potential Evapotranspiration (mm)	
				Bush	Penicuik
Whole area		117.7	261.7		
Strips	379.4	56.5	322.9	302.1	316.6
Ditches		260.7	118.7		

TABLE 7 : Separate water balances for the whole area and for its two component parts, i.e. ditches and strips, during the 1980 growing season.

ditch and strip components of the whole area yielded by the method during this time. Water balance calculations were again performed assuming water storage variations to be negligible as it has already been shown that water table levels were similar at the beginning and end of the period. Comparing the results of Tables 6 and 7, it can be seen that the pattern of evapotranspiration distribution over the different areas is very similar in both cases. The independent estimates of evapotranspiration from the strips shown in Tables 6 and 7 have a percentage deviation between them of 1 %. However the corresponding independent estimates of evaporation from the ditches have a percentage deviation between them of 43 %. As the values of actual evaporation from the ditches are not big, any small errors in the data used can introduce sizeable percentage errors on the results of the calculations.

In spite of the errors involved in the separate water balance calculations for strips and ditches, the good agreement between the results shown in Tables 6 and 7 indicates that the method used is probably not much in error.

After being tested for this short 5 month period, the method was then used to estimate evapotranspiration from strips and evaporation from ditches during the frost free seasons of the three years of records (Table 8). The results obtained confirm again the pattern described earlier. Evapotranspiration from the strips again has

Period	16/3/77 - 21/11/77					27/3/78 - 4/12/78					2/4/79 - 12/11/79				
	Rain (mm)	Flow (mm)	Actual Evapot. (mm)	Pot. Evapot. (mm)		Rain (mm)	Flow (mm)	Actual Evapot. (mm)	Pot. Evapot. (mm)		Rain (mm)	Flow (mm)	Actual Evapot. (mm)	Pot. Evapot. (mm)	
				Bush	Penicuik				Bush	Penicuik				Bush	Penicuik
Whole Area		410	277				308	304				190	280		
Strips	687	342	345	388	474	612	227	385	361	404	470	155	315	382	397
Ditches		567	120				496	116				271	199		

TABLE 8 : Separate water balances for the whole area and for its two component parts, i.e. ditches and strips, during the three frost free seasons covered by the records.

values close to Penman potential evapotranspiration. Percentage deviation between actual evapotranspiration from the strips and potential evapotranspiration from Bush and Penicuik ranged from + 7 % to - 27 %. Actual evaporation from ditches, however, has significantly lower values than potential evapotranspiration, ranging from 48 % to 75 % lower than potential evapotranspiration from Bush and Penicuik. It is important to mention that evapotranspiration from the whole area is simply a weighted mean of evapotranspiration from its two component parts, i.e. strips and ditches.

As was previously mentioned (see 2.2.1), other methods were also used to estimate separately actual evapotranspiration from areas occupied by strips. If results to be derived from the lysimeter method and from the water table fluctuations method confirm the results already shown, this will certainly mean that the conclusions are not much in error.

As was shown in Part 2 (see 2.2.2), a preliminary experiment with two lysimeters indicated that actual evapotranspiration was not reduced below its potential value, even in lysimeters allowing free drainage. During the growing season of 1980, five lysimeters were used for a further check of these preliminary conclusions. As was also shown (see 2.2.2) lysimeter 1 was yielding, during 1979, very low evapotranspiration estimates due to the effects of waterlogging periods on the physiological vigour of its vegetation sample. It was visually noticeable that the vegetation sample of lysimeter 1 never recovered from these physiological stresses and thus data from this lysimeter will be ignored in the following analysis. All the four lysimeters that gave useful data were allowing free drainage and the water table level was not controlled in any one of them. Appendix 5 shows weekly evapotranspiration yielded by the four lysimeters, from the 29th April to the 3rd November 1980. For the final part of this period, no data are available from two of the lysimeters, due to damage to their hydraulic weighing systems. Table 9 summarizes monthly evapotranspiration data yielded by the lysimeters. Lysimeter 2 had been used during the preceding growing season and its vegetation sample suffered some adverse effects during the winter period of 1979/1980. During May and June of 1980 its Calluna plant was still showing a purple colour while the surrounding area had already an intense green colour. This vegetation sample recovered later and by the end of June 1980 was already showing a similar colour to that of the surrounding vegetation. Data for May and June 1980 from this lysimeter will not be considered in the following discussion. Table 9 shows that for most of the period of record, lysimeters 2, 3 and 4 yielded evapotranspiration estimates fairly close to Penman potential evapotranspiration. Lysimeter 5 was yielding slightly lower evapotranspiration values. This can be explained by the fact that lysimeter 5 had the worse vegetation sample of all the lysimeters.

Month (1980)	Actual Evapotranspiration (mm)				Potential Evapotranspiration (mm)	
	Lysimeter No.				Bush	Penicuik
	2	3*	4	5*		
May	53.8**	83.1	83.2	66.1	79.7	-
June	60.4**	66.7	70.9	60.0	71.8	77.3
July	65.3	67.1	66.1	54.8	62.4	68.3
Aug.	50.8	59.0	61.5	-	53.6	55.7
Sept.	39.2	-	48.4	-	34.6	35.6
Oct.	30.6	-	36.8	-	13.5	15.4

* Lysimeter with taller vegetation. Data corrected for windy and rainy periods.

** Vegetation sample recovering from previous winter stresses.

TABLE 9 : Monthly evapotranspiration results yielded by the lysimeters during the 1980 growing season.

In spite of some scatter, the data presented in Table 9 show reasonable consistency. Most of the discrepancies can be explained by the rain trap phenomenon (see 2.2.2) and by noticeable differences in the physiological vigour of their vegetation covers. During October 1980, lysimeters 2 and 3 were yielding actual evapotranspiration estimates significantly higher than potential evapotranspiration estimates. During this period, any small error in the lysimeter readings will represent a big percentage of the small amount of total evapotranspiration. Table 10 shows average monthly values of actual evapotranspiration from the lysimeters as well as the average total evapotranspiration for the six month period. Average monthly values were calculated as the simple arithmetic mean of the results yielded by the different lysimeters. Evapotranspiration from lysimeter 2 for the months of May and June was ignored in the calculations. Table 10 shows that monthly evapotranspiration from the lysimeters is always fairly close to potential evapotranspiration estimates, the only significant exception occurring during October. Total evapotranspiration from the lysimeters, for the six month period, is 3 % higher than potential evapotranspiration for Penicuik and 8 % higher than potential evapotranspiration for Bush.

Lysimeter data for the growing season of 1980, confirms the preliminary conclusion that even in freely drained lysimeters actual evapotranspiration is not reduced below its potential value. According to the

Month (1980)	Rainfall (mm)	Actual Evapotranspiration (Average from Lysimeters) (mm)	Potential Evapotranspiration (mm)	
			Bush	Penicuik
May	26.2	77.5	79.7	- (79.7)
June	111.5	65.9	71.8	77.3
July	84.0	63.3	62.3	68.3
Aug.	99.3	57.1	53.6	55.7
Sept.	58.4	43.8	34.6	35.6
Oct.	115.9	33.7	13.5	15.4
TOTAL	495.3	341.3	315.5	332.0

TABLE 10: Average monthly evapotranspiration from the lysimeters during the 1980 growing season.

conclusions drawn in section 2.2.2, this also means that the areas occupied by strips, in which moisture conditions are even more favourable, are also evapotranspirating at the potential rate.

As has already been mentioned (see 2.2.1), the water table fluctuations method did not seem to be applicable in the study area. However, a consideration of the reasons why that is so can contribute to a better understanding of the behaviour of evapotranspiration from the strips. Figure 18 shows typical water table fluctuations during an almost rainless week, with a total rainfall amount of 1.9 mm. Water table fluctuations show a typical pattern with a day time fall and a slight night time rise. Such night time rises do not necessarily mean that there is some groundwater recharge from the surroundings (see 2.2.1). To apply the water table fluctuations method, the specific yield of the soil must be known (see 2.2.1). Specific yield values for different soil depths were calculated by a simplified version of the method described by Vorob'ev (1963). According to Vorob'ev, specific yield, termed by him as coefficient of drainage, can be computed from water table responses to rainfall events, using the formula:

$$Sy = h/\Delta z \qquad (22)$$

in which Sy is the specific yield, h is the precipitation (mm) and Δz is the water table reaction to that precipitation (mm). According to Vorob'ev the values of specific yield computed in this way are usually too high because part of the total precipitation is intercepted either by

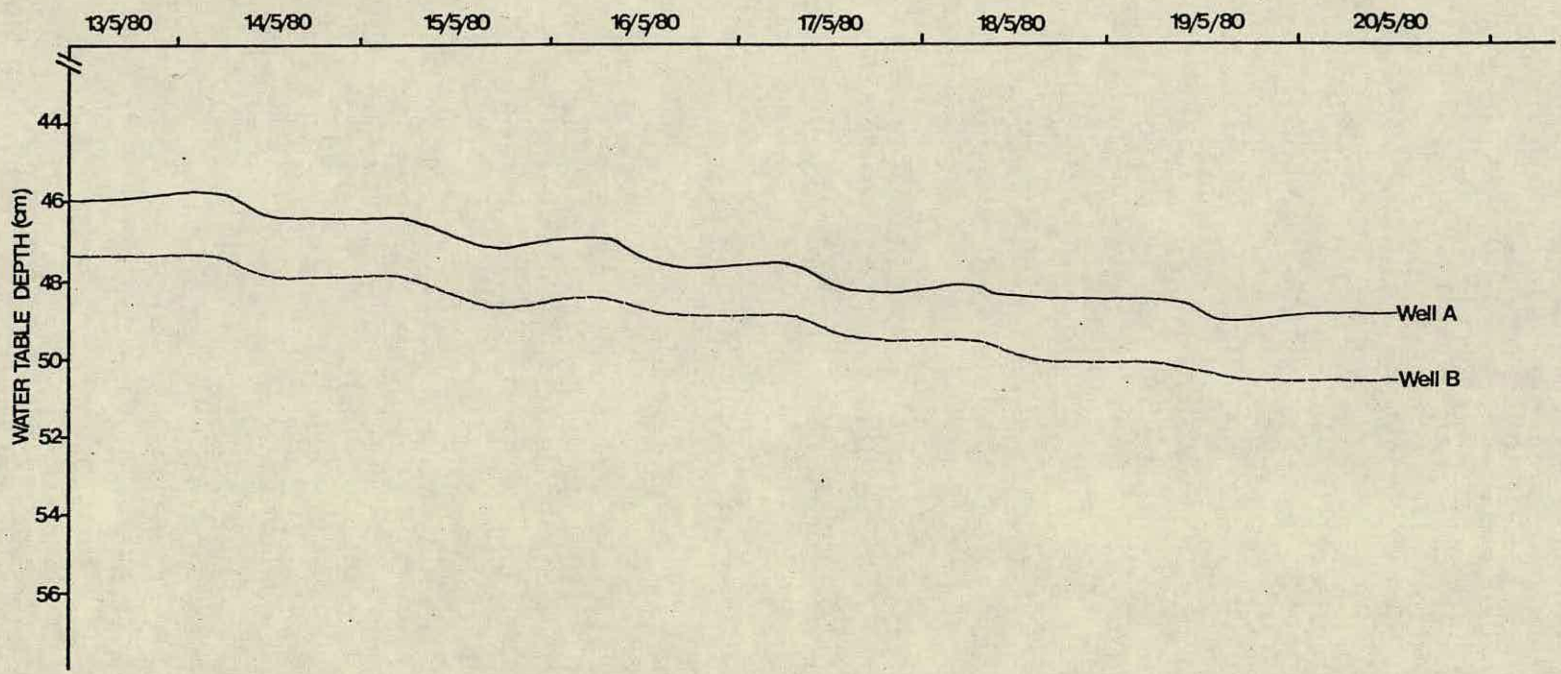


Figure 18 : Typical diurnal fluctuations of the water table during a rainless week.

the plant cover or by the surface layers of the soil and hence does not reach the water table. These errors are kept to a minimum if the event analysed is preceded by a wet period. On the other hand a rise in the water table in response to a rainfall event is a balance between water gained from rainfall and water lost by natural drainage. According to Vorob'ev, during low intensity and long duration rainfall events the amount of water lost by drainage can be appreciable and can introduce sizeable errors into the computed values of specific yield. The straight application of equation (22), needs the availability of long periods of records in which a significant number of short-duration rainfall events is preceded by wet periods. Vorob'ev (1963) developed a method to compute specific yield values for the different peat layers, in which the mean value of intercepted precipitation is taken into account. In the present case the data base was not big enough to allow the application of the method exactly as described by Vorob'ev. Equation (22) was directly applied, but only to short-duration rainfall events which were preceded by a wet period. Data from the two wells equipped with water level recorders were treated separately. Figure 19 shows specific yield values plotted against depth below ground surface. Depth below ground surface for each event was computed as the arithmetic mean of the initial and final water table depth of the corresponding water table rise. Figure 19 shows that specific yield is fairly uniform for most of

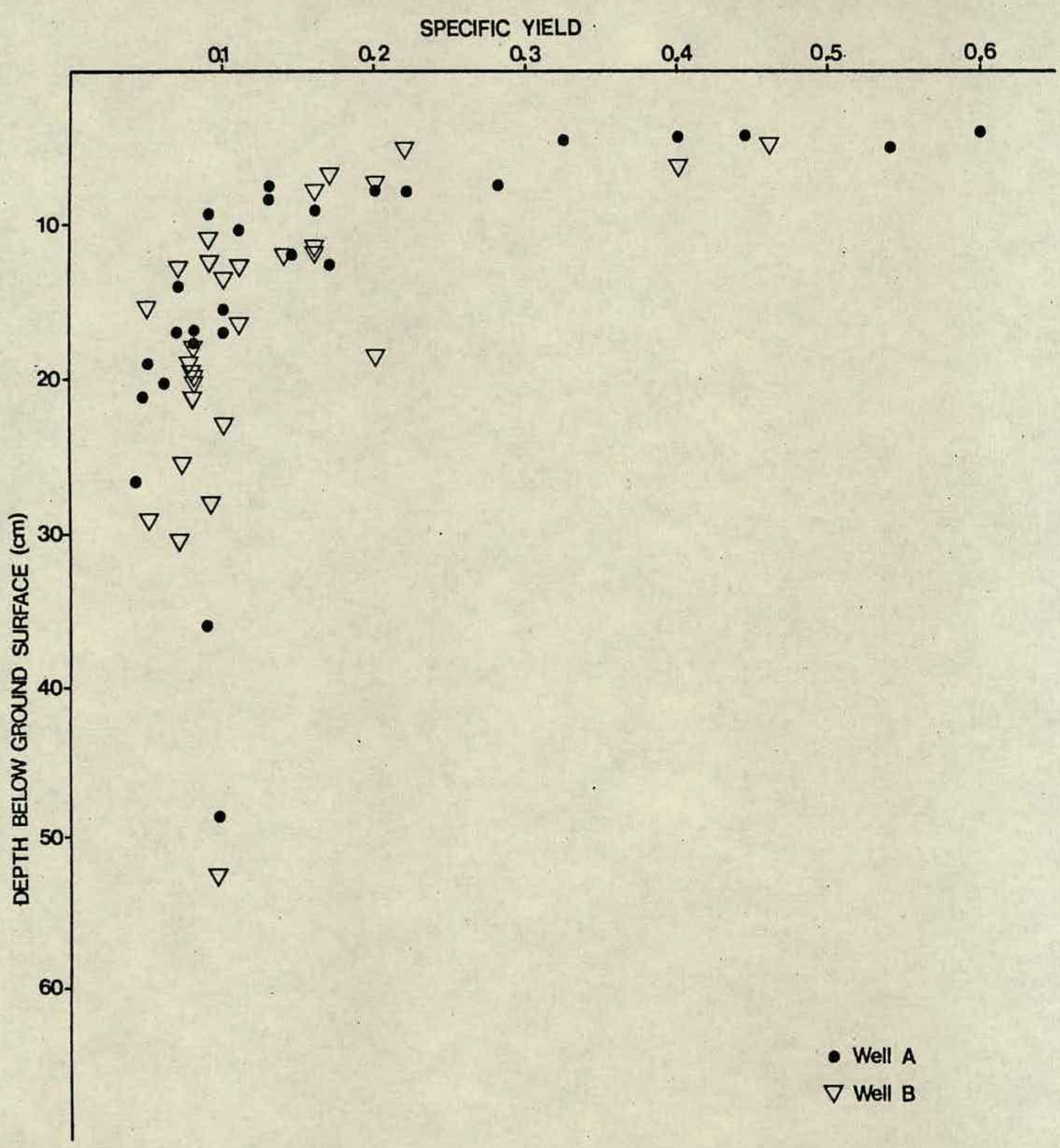


Figure 19 : Relationship between the specific yield of the peat and the depth below ground surface.

the peat profile, with values ranging from 0.05 and 0.1, and only increases substantially in the very top layers. This variation of specific yield with depth has a similar shape and a similar range of values to Vorob'ev's data for the Tarmanskoye, Uzaklinskoye and Talagul'skoye swamps. Boelter (1975), found specific yield values ranging from 0.08 for decomposed peat to 0.86 for live, undecomposed mosses. Specific yield values shown in Figure 19 are thus in good agreement with the results presented by other authors.

Assuming an average value of specific yield of 0.08 for the lower layers of decomposed peat, equation (7) (see 2.2.1) can now be used to compute actual evapotranspiration from the water table fluctuations shown in Figure 18. During the rainless day of 15th May, 1980, the day time water table fall was of about 10 mm and its night time rise about 5 mm. Equation (7) yields for that day an actual evapotranspiration value of (10 + 5) x 0.08 = 1.2 mm. For this same period lysimeters 3, 4 and 5 were yielding mean daily evapotranspiration rates ranging from 3.4 to 3.6 mm/day (see Appendix 5). This clearly shows that the water table fluctuations method substantially underestimates the actual evapotranspiration rates from the strips. This fact can only be explained if water losses from the soil, due to evapotranspiration, are not being completely compensated for by the upward transmission of water from the water table. If this happens moisture deficits should develop in the top peat layers.

This is in fact demonstrated by the water table responses to rainfall during dry periods. Figure 20 shows that, during the week June 3 - 10, 1980, for example, 23 mm of rainfall was needed to restore subsurface moisture deficits before any significant recharge of groundwater was observed. Ahti (1979, 1974) observed the same phenomenon in a forested drained peatland in Finland. According to him, for deep water table levels, evapotranspiration easily exceeds the upward water transmission capacity, and precipitation does not reach the water table. Hence, some precipitation leaves the profile as surface runoff or evapotranspiration before reaching the water table. The conclusions drawn by Ahti and the results of the present work show that during dry periods the water balance of the upper peat layers of the strips is partially independent of water table upward recharge. As was shown earlier, results from the lysimeters indicated that even soil-vegetation samples with no recharge from the water table have actual evapotranspiration rates close to the potential rate. During the entire growing season of 1980 water retained against gravity in the soil samples of the lysimeters was sufficient to keep actual evapotranspiration at its potential rate. During this period, total rainfall largely exceeded total evapotranspiration (see Table 8).

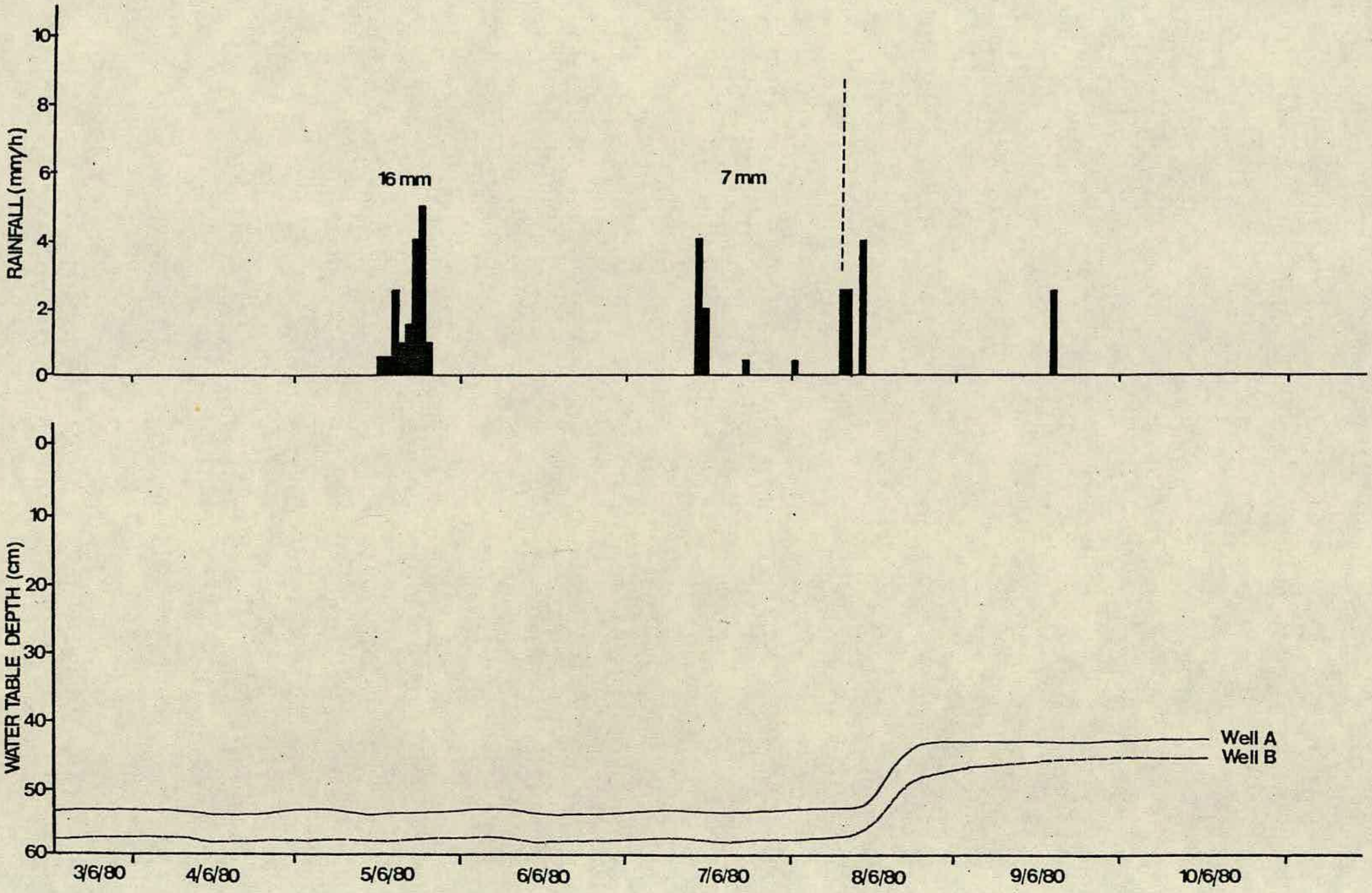


Figure 20 : Water table responses to rainfall after a dry period.

3.2.3 Discussion

As was shown earlier several independent methods were used to estimate actual evapotranspiration from the whole area as well as from its two component parts, i.e. strips and ditches.

The water balance method was applied to the whole area and to the runoff plots. The results yielded by this method may be affected by possible errors in rainfall and runoff data (see 2.2.1). Possible errors in rainfall and runoff measurements have been previously discussed in section 2.1. Errors in runoff measurements were found to be particularly important during frost affected periods. Water balance calculations were also done assuming that variations in storage were zero for all the periods used. If this assumption is not true then derived evapotranspiration values will contain errors from this source, particularly for short periods of time. However, for short periods care was taken to verify that water table levels were similar at the beginning and end of each period. Furthermore, as was shown in section 3.2.2, specific yield of the peat in this area is very low and has an average value of approximately 0.08 for most of the profile. Only in the very top layers does specific yield increase substantially. According to Ward (1975), specific yield, termed in his work as coefficient of storage, of an aquifer is defined as the volume of water which an aquifer releases from, or takes into, storage per unit surface area of the aquifer and per unit decline or rise of the water table level. If this volume of water is expressed in millimetres, a specific yield of 0.08 means that a water table level variation of 1 mm corresponds to a gain or loss of 0.08 mm of water. In this case, even a significant water variation of, for instance, 20 cm corresponds to a real change in storage of only $\pm$ 16 mm. Furthermore the above considerations are only applicable to the areas of strips. Ditch areas have certainly much lower water storage changes. The overall water storage change for the whole area will be the weighted mean of water storage changes in its ditch and strip components and thus will certainly have even lower values than the ones referred for the strips.

The above considerations on water storage variations are only valid if the water table depth is a good indicator for the moisture content of the all peat profile. This assumption has been generally used in peat hydrology (i.e. Romanov 1968b, Bay 1967) and is supported by the experimental results of Heikurainen et al (1964). However, the recent results of Ahti (1979, 1974) together with the results of the present work show that, during dry periods, the water balance of the topmost layer of the strips of drained peatlands is partially independent of the water table upward recharge. Ahti (1979, 1974), using tensiometers, clearly showed that, in certain cases, the water table is a poor indicator of the moisture content of the upper peat layer. According to him, care must be taken when the water table depth is used to estimate water storage variations during very short periods. However, he also found that, for longer periods of calculations, the water table reflects reasonably well the moisture conditions.

The above considerations indicate that the general assumption followed in this study that water storage variations can be neglected in most water balance calculations, is probably not causing important errors in the results, particularly if the water table level was checked and had similar values at the beginning and end of each period of calculations. For shorter periods some errors may be introduced when the water table depth is assumed to be a good indicator of the water storage. However, water table levels were the only available data that could be used for this purpose. Furthermore, it must be also remembered that the shortest period used on the water balance calculations was five months.

The method used to estimate separately flow originating either from the strip or from the ditch components of the experimental site is based on simplifications of the real hydrological behaviour of the area and this can also introduce errors into the results. Nevertheless, the method seems to yield fairly consistent results which are in general agreement with those from other sources. This tends to indicate that the assumptions on which the method was based are probably not much in error.

The lysimeters used in the present work are of a very small size and thus questions on the representativeness of their results can be raised. However, this problem was partially overcome by using five replicates during the growing season of 1980. Overall the different lysimeters yielded fairly consistent results. Most of the discrepancies between results of different lysimeters could be explained by the rain trap phenomenon (see 2.2.2) and by noticeable differences in the physiological vigour of their vegetation covers.

One of the biggest problems concerning evapotranspiration data analysis in this project occurs when actual evapotranspiration has to be compared with potential evapotranspiration. Penman potential evapotranspiration estimates from the two nearby meteorological stations had big differences between them at times. For instance, during the period 16 March to 21 November 1977, the percentage deviation between the two independent estimates of potential evapotranspiration amounted to 22 %. Potential evapotranspiration was not measured at the site because of the time it would have taken to install and operate a suitable meteorological station. Furthermore, meteorological data from the nearby long-term stations of Bush and Penicuik were initially thought adequate for this purpose. In retrospect, however, it is accepted that more reliable data should have been obtained by installing a meteorological station at the site.

According to Ward (1975), probably all the methods for determining evapotranspiration are in some error and there is no absolute standard against which results from given formulae or instruments may be assessed. It seems then, that it would probably be erroneous to try to derive precise quantitative conclusions from the results presented. Nevertheless, the results yielded by the different methods showed a degree of consistency that seems good enough to justify some general conclusions about the pattern of evapotranspiration distribution over the different component parts of the experimental area.

The results of all the methods used indicate that the very low values of the evaporation from the ditches together with the potential values of the evapotranspiration from the strips result in an average evapotranspiration from areas integrating these two components which is lower than potential evapotranspiration.

As was discussed earlier (see 1.1), several authors have found that actual evapotranspiration from peatlands was greatly reduced after drainage for forestry purposes (i.e. Heikurainen, 1975; Mustonen and Seuna, 1975; Seuna, 1974). The results of the present work also show that actual evapotranspiration from the whole experimental site is systematically lower than potential evapotranspiration and in this respect they agree with the results of previous experiments. However, results from the present work suggest that the main factor explaining such evapotranspiration reduction after drainage is the creation of new sheltered and almost bare ditch areas. In a sense, these conclusions contrast with previous explanations of the same fact which have generally assumed that such a decrease is caused primarily by a drop in the water table and by a consequent destruction of the natural bog vegetation (Mustonen and Seuna, 1975; Seuna, 1974).

The fact that the evaporation from the ditch areas is very low can be supported by a number of different reasons. One is that these areas are sheltered from both air movement and solar radiation and thus specific micro-climatic conditions should be expected to develop within them. Verma and Cermak (1974) studied, in a wind tunnel, the distribution of local mass-transfer coefficients over saturated corrugated surfaces. They found that the build up of high humidity in the vortices formed inside the furrows tended to reduce moisture transfer. As a result, the evaporation loss from the bottom of the furrows was reduced, this reduction being greatest in deep furrows. Similar reductions in moisture transfer from sheltered surfaces have also been observed in other situations. For instance, Bonython (1950), cited by Rijtema (1965), showed that the evaporation from pans decreases when the water level inside the pan drops. On the other hand, Oke (1978) states that the furrow geometry can work as a radiative trap for both direct solar radiation and the outgoing long-wave radiation, which tends to increase soil temperature in a ridge and furrow system. According to him this trapping of short and long-wave radiation will depend on the spacing and orientation of the furrows. The complexity of the evaporation phenomenon from the ditch areas is further increased by the fact that the water table depth below the ground surface varies from point to point along a ditch cross section.

As was previously mentioned, the ditches have almost no vegetation cover and make up 30 % of the total area of the site. During some summer periods, when there is no outflow from the area, both the ditch slopes and the ditch bottoms dry out and then will only loose water to the atmosphere by evaporation from their almost bare and dry peat surfaces. Under these conditions, eventual soil moisture deficits are liable to further reduce the evaporation from such areas. The longest continuous period of time during which no outflow was observed lasted for 7 weeks, from 19 June to 6 August 1979. Shorter similar periods occurred during the summer of each year of records (see Appendix 2). Ivitskii (1968a, 1968b), during experiments with lysimeters, found that even for shallow water tables (20 cm below the ground surface), evaporation from bare peat was 34 % lower than evapotranspiration from a peat sample with a cover of grass.

When water is flowing on the ditch bottoms, some evaporation will occur from the surface of the running water. Under these conditions eventual evaporation restrictions from the ditch bottoms will be mainly due to the already discussed reductions of moisture transfer from sheltered areas.

The results of the present study, according to which ditch evaporation is substantially lower than potential evapotranspiration, are thus in general agreement with most of the considerations drawn in the previous paragraphs.

Results of previous studies on undrained peatlands and recently drained peatlands for agricultural purposes can only be compared with those obtained in this work for the strips between the ditches. In fact both undrained peatlands and recently drained peatlands for agricultural purposes have usually a more or less uniformly vegetated ground surface which can only be compared with the vegetated strip component of the present study area.

It was previously seen (see 1.1) that after drainage for agricultural purposes actual evapotranspiration from peatlands is greatly reduced (Zubets and Murashko, 1975; Klueva, 1975; Bulavko and Drozd, 1975; Bulavko, 1971; Romanov, 1968b). It was also mentioned (see 1.1) that this is usually explained by the fact that when water table drops after drainage, natural peat vegetation is adversely affected if not completely destroyed (Bulavko, 1971). According to Boelter and Verry (1977) and Romanov (1968b) when the water table drops to ~30 cm below the ground surface the capillary fringe does not reach the surface mosses and herbaceous roots and as a result evapotranspiration is drastically reduced. However, and as was also mentioned (see 1.1), actual evapotranspiration recovers again when the drained areas are occupied by agricultural crops (Zubets and Murashko, 1975; Moklyak et al, 1975; Kubyshkin, 1975; Bulavko, 1971).

The above considerations indicate that actual evapotranspiration from uniformly vegetated peatlands can be influenced by two main factors: the moisture content of the upper peat layers, which is considered to be very much related to capillary rise from the water table, and the vegetation characteristics of the surface cover.

In the present case the natural peat vegetation had the particular feature of including the species Calluna vulgaris which has the characteristic of growing better in well drained peatlands than in waterlogged peatlands (Gimingham, 1972; Department of Agriculture and Fisheries for Scotland, 1965, 1964). This being so, at least one component of the original peat vegetation of the site reacts to drainage in an opposite way from that found for other peat vegetation types. In the present study area, mosses and other species were certainly adversely affected on the strips by the water table drop after drainage but this was at least partially compensated by the luxuriant Calluna dominated heather cover which developed afterwards. From these considerations it is reasonable to expect that, in the present case, evapotranspiration from the strips would not be reduced after drainage as much as has been found in other drained peatlands where the whole natural vegetation was adversely affected by drainage. In a sense, this recovering of Calluna after drainage should work in a similar way to the occupation of drained peatlands by agricultural crops. Furthermore, fertilizers are usually applied when the strips are planted with trees and this certainly speeds up the growth of <u>Calluna vulgaris</u>. In a situation like this it is not surprising, therefore, to find that actual evapotranspiration from the strips between ditches has values very close to those for Penman potential evapotranspiration.

The fact that actual evapotranspiration from the strips between ditches is close to potential evapotranspiration, does not necessarily mean however that it equals actual evapotranspiration occurring before drainage. In fact, it has been shown that actual evapotranspiration from undrained peatlands can be significantly higher than evaporation from open water (Nichols and Brown, 1980; Sturges, 1968a). This being so, the strips can be evapotranspirating at a Penman potential rate and this can still consitute a reduction when compared with actual evapotranspiration before drainage. As was mentioned earlier (see 1.1), no direct comparisons between drained and undrained areas could be made in the present study. On the other hand, the conclusions of the present study are based mainly on an intensive study done during two growing seasons, 3 years after drainage had been carried out. It is possible that immediately after drainage evapotranspiration from the strips had lower values than those measured during the most intensive period of study. There are no data on the period of time taken by <u>Calluna</u> to recover, after the inevitable initial impact of drainage on the other vegetation species of the original bog. However, the results of this study show that this recovery period was fairly short and certainly less than 3 years. As was mentioned previously (see 2.1) the trees planted in the area are still very small and probably have a negligible influence on the evapotranspiration from the strips. Furthermore, some of the results on the evapotranspiration from the strips were obtained in areas from which small trees were completely absent. This is the case of the results obtained from the lysimeters and from the runoff plots.

As was mentioned earlier, together with vegetation type, soil moisture is the other factor that can restrict the evapotranspiration from the strips below its potential value. It has been shown (see 3.2.2) that during dry summer periods, strip evapotranspiration exceeds upward water transmission from the water table and that, during such periods, the water balance of the upper peat layers is partially independent from this upward groundwater recharge. This being so it is important to have an idea of the amount of water that can be retained against gravity by the surface peat layers. According to Lundin (1975) the surface layer (0 - 50 cm) of a drained peat retains 355 mm of water when it is at field capacity. At the temporary wilting point 150 mm of water is retained by the same layer. Lundin further indicates that the lower limit of the optimal range of moisture for agricultural crops occurs when the water content of the top 50 cm of a peat profile is 250 mm. This being so it is necessary that the 0 - 50 cm peat layer loses some 105 mm of water below field capacity before the lower limit of the optimal moisture for agricultural crops is reached. Boelter (1964) and Sturges (1968b) have published data on water content at a number of water suctions for different layers of different types of peat. Dooge (1975), summarizing the Boelter's work, states that partially decomposed moss peat has moisture contents of 64 % at field capacity (suction of 0.1 bar) and 21 % at wilting point (suction of 15 bar). He also states that decomposed peat has moisture contents of 72 % at field capacity and 22 % at wilting point, all moisture contents being expressed on a percentage volume basis. The total amount of water retained against gravity by the upper peat layers will obviously depend on the relative proportions of partially decomposed and decomposed peat. As was previously mentioned, Cuttle (pers. comm.) found that in the present experimental site the top layer of partially decomposed Sphagnum peat has an average depth of only 15 cm and is underlain by a layer of well decomposed peat.

The above considerations indicate that even a freely drained peat will usually have a good holding capacity for water. On the other hand, the uniformly wet characteristics of the local climate must also be kept in mind. According to Birse (1971), the experimental site is on the transition between two bioclimatic sub-divisions: the humid sub-division, for which annual potential water deficit varies from 25 to 75 mm, and the very humid sub-division, for which annual potential water deficit varies from 0 to 25 mm. According to the points made earlier it should be expected that even freely drained peat samples would hold enough water to prevent significant restrictions on evapotranspiration during most dry periods. The results from the lysimeters for the 1980 growing season (see 3.2.2) confirm that there was enough water for actual evapotranspiration from freely drained soil-samples to occur at its potential rate throughout this period.

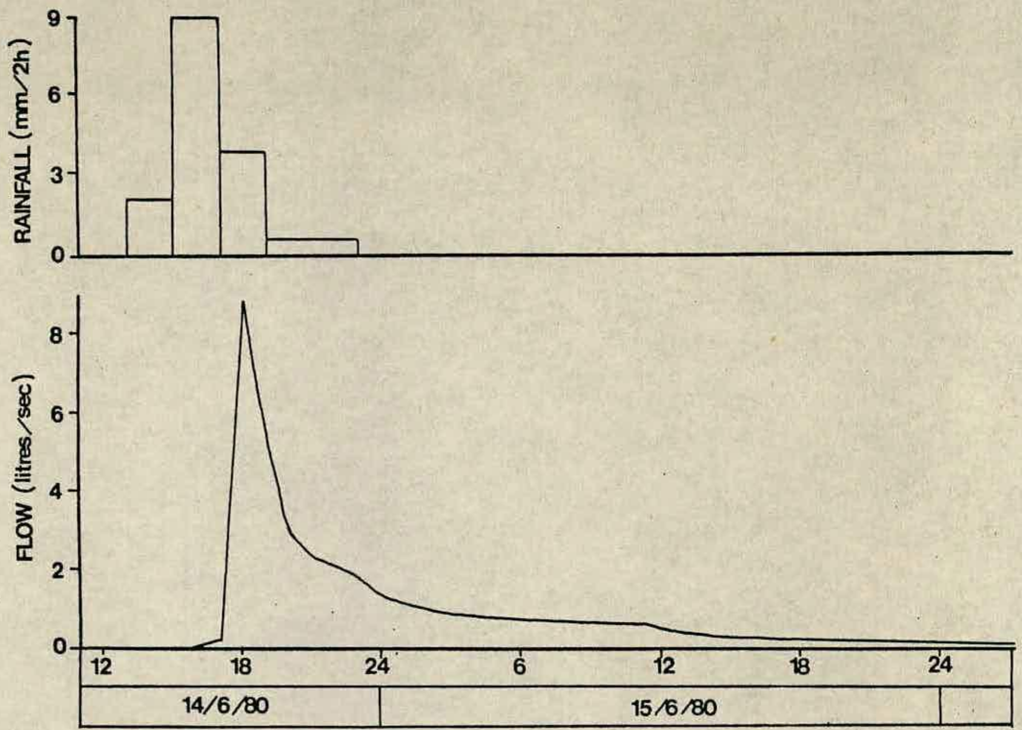
Overall the conclusion that strip evapotranspiration in the study area occurs at the potential rate as determined by the Penman equation seems to be based on results and reasoning in general agreement with theoretical considerations. However, the results of the present study may be criticized for being based on the assumption that the ditches and the strips are fairly uniform areas each of which has a typical uniform behaviour. This assumption is not completely true as can be exemplified by the existence of bare peat ridges on the boundaries of the strips. Also, the ditch area is certainly a very complex system with great heterogeneity along each cross section. However, any hydrological work must be based on some simplification of reality as it is impossible to cover the immense variety of micro-environments present in any small area. It is felt however that the simplification made in this study has been the correct one, and that the major differences requiring study are those between strips and ditches rather than those internal to these quite distinct environments.

3.3 Runoff Processes

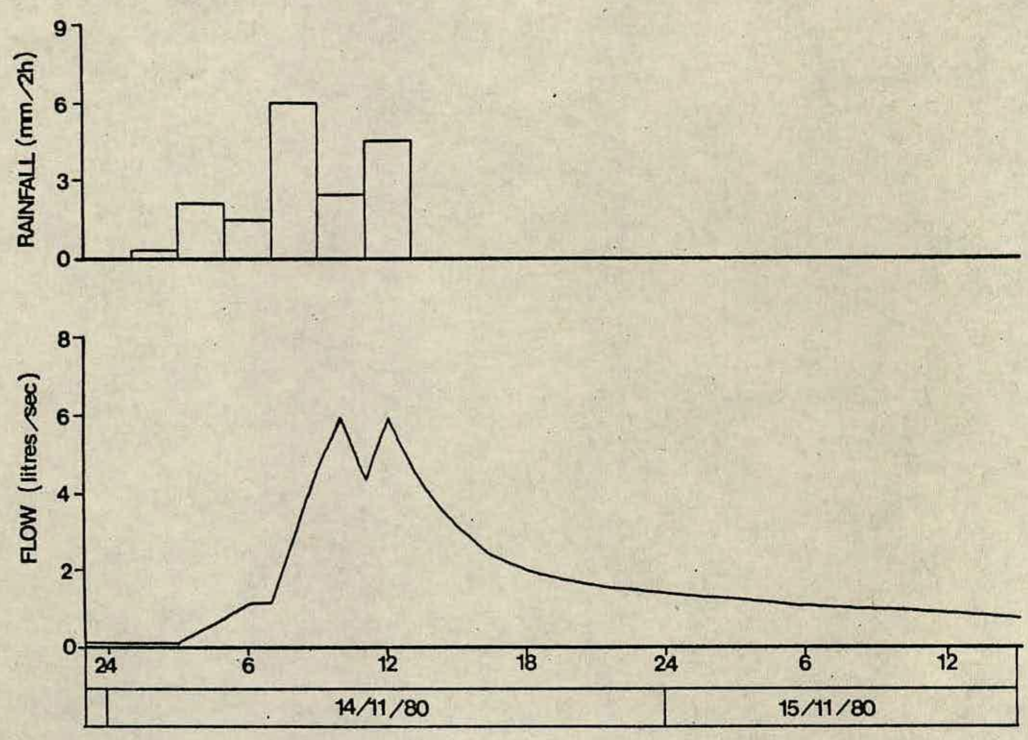
3.3.1 Preliminary Considerations

It was mentioned earlier (see 1.1) that determination of the predominant flow processes in the study area would probably help greatly in understanding its hydrological behaviour. Before going into any detailed analyses of these different flow components, it is important to consider first the general characteristics of the outflow hydrographs from the site. Storm hydrographs measured at the V-notch weir (Figure 21), show sharp and well defined peaks as well as long recession limbs with a very small rate of decay. The recession limbs of the hydrographs usually remain above the pre-storm discharge level for a long time which indicates a temporary storage and slow release of water. The recession limbs of some growing season hydrographs (Figure 21a) are stepped during the day time probably on account of evapotranspiration. As a consequence the recession limbs of growing season hydrographs drop more quickly than those of dormant season hydrographs. Bay (1969), studying the response of some undrained peatland watersheds in Minnesota, noticed similar characteristics on the recession limbs of growing season hydrographs.

3.3.2 Flow Components from Areas Drained by 60 cm Deep Ditches



(a)



(b)

Figure 21 : Typical hydrographs recorded at the site outlet.

(a) growing season

(b) dormant season

It was mentioned previously (see 2.3) that information on flow generation processes was mainly derived from the runoff plots and from the piezometer nests, and that these instruments were located on areas drained by 60 cm deep ditches. Some preliminary conclusions on flow processes, drawn from the runoff plots data, were already described in Section 3.2.2. It was then mentioned that during dry periods stormflow was only originated by rain falling directly into the ditches. In some extremely dry situations, when subsurface soil moisture deficits occur, both on the ditches and on the strips between ditches, even heavy rainfall events may be completely stored in the subsurface peat layers and no flow is originated. For instance, on the 5th of June 1980 a storm of 15.5 mm produced no outflow from the uncovered runoff plots. On the other hand, it was also shown that during wet periods the ditches work as impermeable areas and there is also a significant flow contribution from the strips.

During wet periods, when flow from the strips is a significant component of the total flow, different flow processes may occur depending on the prevailing soil moisture conditions.

In Figure 22, an example of discharge hydrographs recorded from the runoff plots is represented together with the rainfall hyetograph and water table variations measured at the centre of the strips between the ditches. During this event the water table rose from an initial

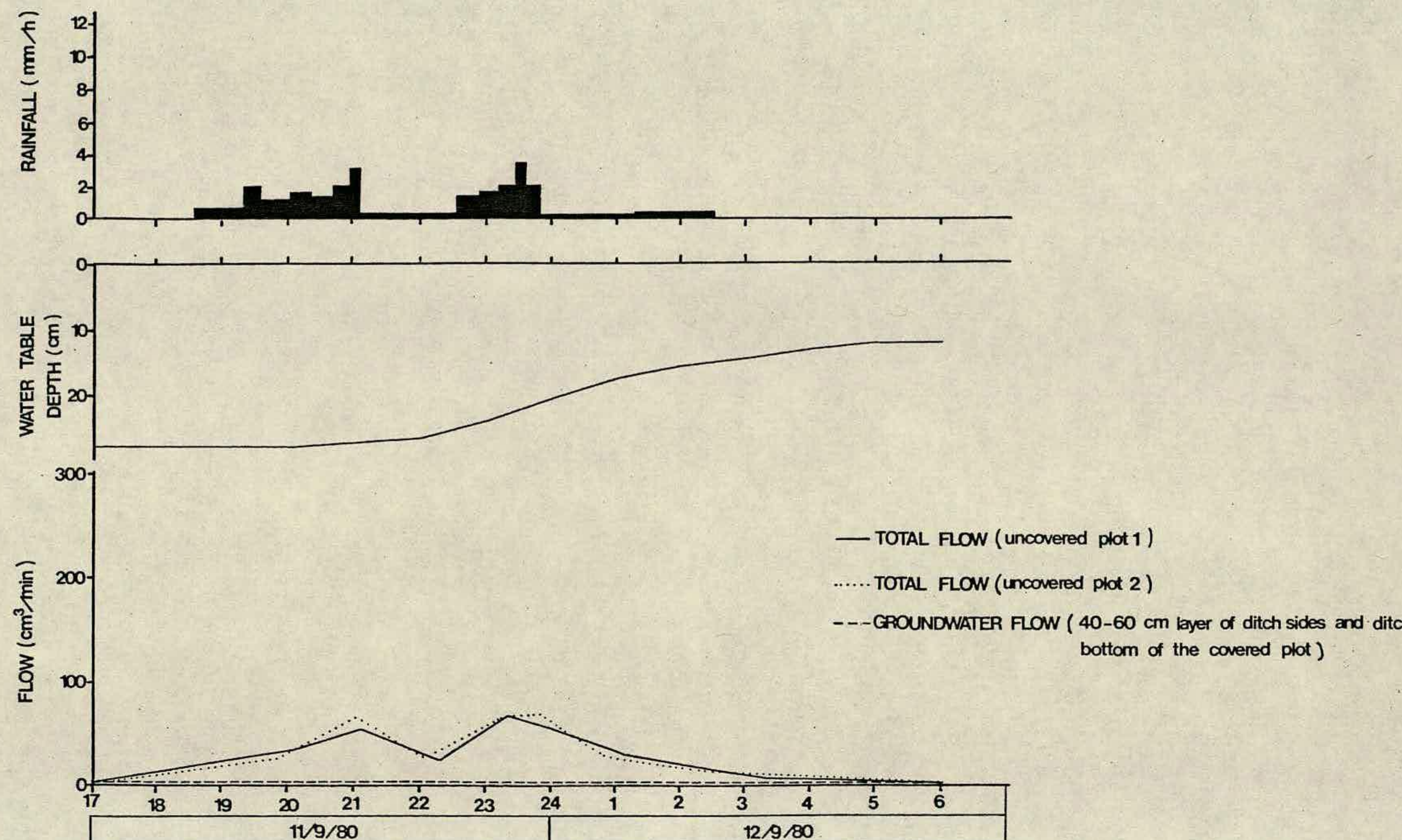


Figure 22 : Rainfall, water table changes and combined hydrographs from the runoff plots on September 11 - 12, 1980.

depth of 28 cm to a final depth of 12 cm. It can be seen that during the entire event the only component of flow from the strips was that from groundwater emerging from the 40 - 60 cm deep layer and from the bottom of the ditch itself. The groundwater flow rate hardly changed during this event in spite of the measured increase in the water table level. Assuming that the strip areas contributing to the uncovered and covered plots behave in a similar way, actual ditch flow will be the difference between the measured total flow and the flow from the strips (see 2.3.2). This being so, it is clear from Figure 22 that the main component of stormflow was flow originating as rain falling directly into the ditches. This kind of flow may be regarded as saturation overland flow as defined by Pilgrim et al (1978) and Chorley (1978). The results from the three different plots agree reasonably well with each other. The hydrographs from the two uncovered plots are fairly similar to each other, and a short time after the rain stopped, the recession limbs follow closely the values of the hydrograph from the covered plot. This tends to indicate that the assumption that the strip components of the different plots behave in a similar way, is probably close to the truth.

Figure 23 shows another very interesting hydrograph recorded at the runoff plots. The rainfall input consists of two major events in rapid succession. The first one is characterized by high rainfall rates and the second one by much lower intensities. This event produced a well

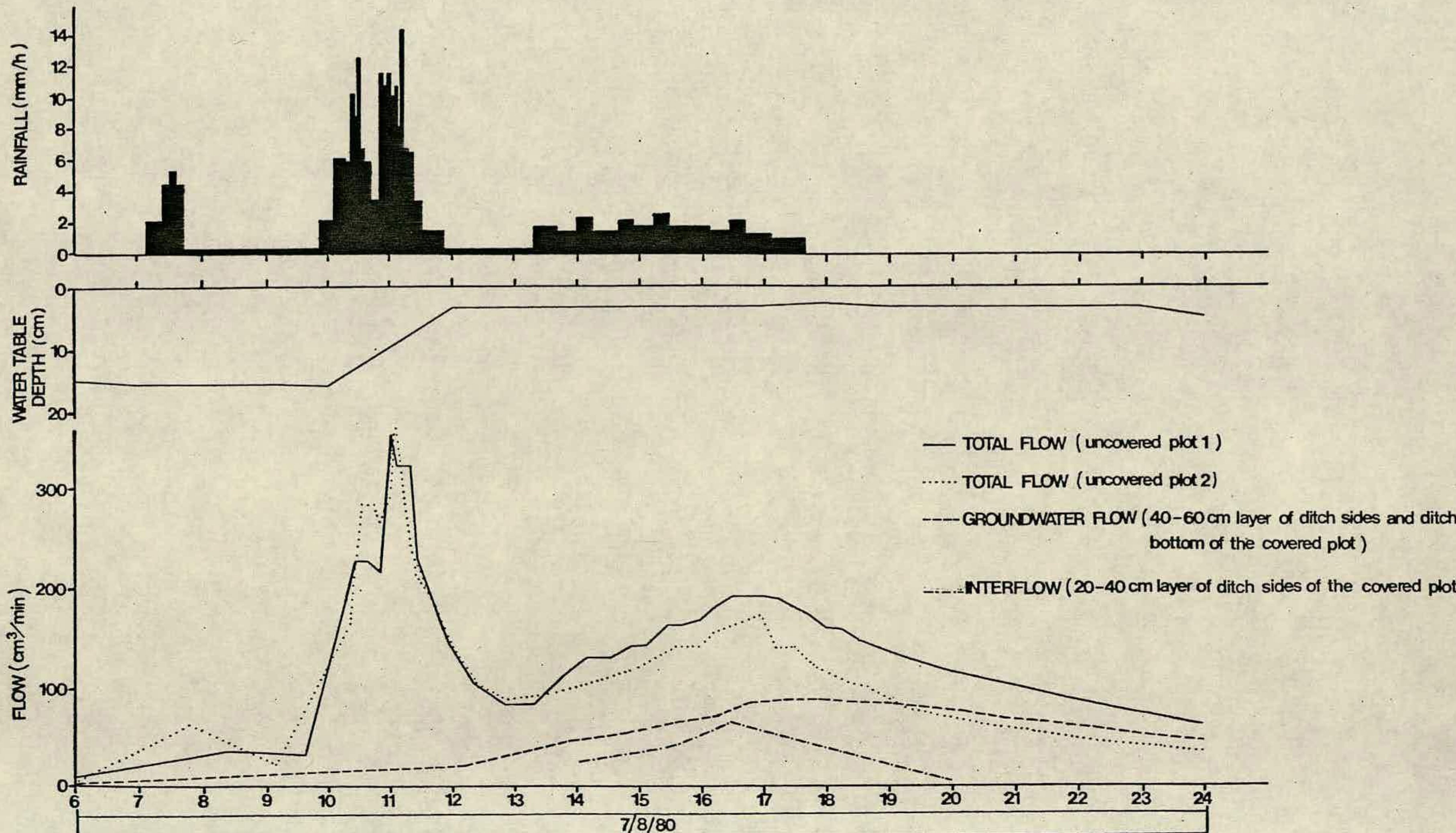


Figure 23 : Rainfall, water table changes and combined hydrographs from the runoff plots on August 7, 1980.

defined double peaked hydrograph. The first part of the storm was preceded by a reasonably dry period. During this heaviest part of the storm the more important flow component was again saturation overland flow originated by direct rainfall into the ditches. During this same period the water table level rose steadily and this was accompanied by a slow, but steady, increase of groundwater flow rate. When the second part of the storm occurred, the soil was much wetter, and water table depth was only 3.5 cm below the surface. During this second period the groundwater flow rate was further increased and a quicker flow component from the strips also emerged from the 20 - 40 cm deep layer of the ditch slopes. This quicker response from the strips will be called interflow hereafter*. It is interesting to note again the reasonably good agreement between the different hydrographs measured from the different plots. However, in this case some differences can be noticed between the values of the recession limbs of the different hydrographs. This tends to indicate that at least in some cases, probably when interflow occurs, flow emerging from the strips may show some spatial variation.

The analysis of this new event indicates again that saturation overland flow from the ditch areas is the major component of stormflow and that quick responses from the strips only occur when the water table level in the strips is very high and almost at the top of the peat profile.

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* This use of the term interflow is more specific than in many hydrological references. It is important to recognize that it will be used hereafter to refer to quick groundwater flow from the main groundwater body.

The general pattern of flow generation during rainfall events preceded by very wet periods is again confirmed by the hydrograph shown in Figure 24. This hydrograph has the characteristic of being caused by a low intensity rainfall event and was preceded by very high water table levels.

During most very heavy storms, interflow always makes a significant contribution to stormflow. If there is no subsurface moisture deficit, a single rainfall event of 25 or 30 mm is usually big enough to raise the water table level almost to the peat surface, even when the initial water table level is low. In fact and assuming an average specific yield value of 0.08 (see 3.2.2), 30 mm of rainfall will correspond to a water table rise of 37.5 cm. On account of this it is difficult to find cases of heavy storms with no interflow component. On the other hand, individual events with more than 20 mm of rainfall are relatively rare and most of the events recorded at the plots were caused by much smaller rainfall amounts. This was one of the reasons why the most common type of flow recorded from the strips was groundwater flow.

The already mentioned fact that interflow probably shows some spatial variability, was confirmed by visual observations of the ditch sides during very wet periods. It was noticed that during such periods interflow was not emerging uniformly over the entire profile of the 20 - 40 cm deep peat layer. Rather water emerged from very localized areas which had a much less decomposed

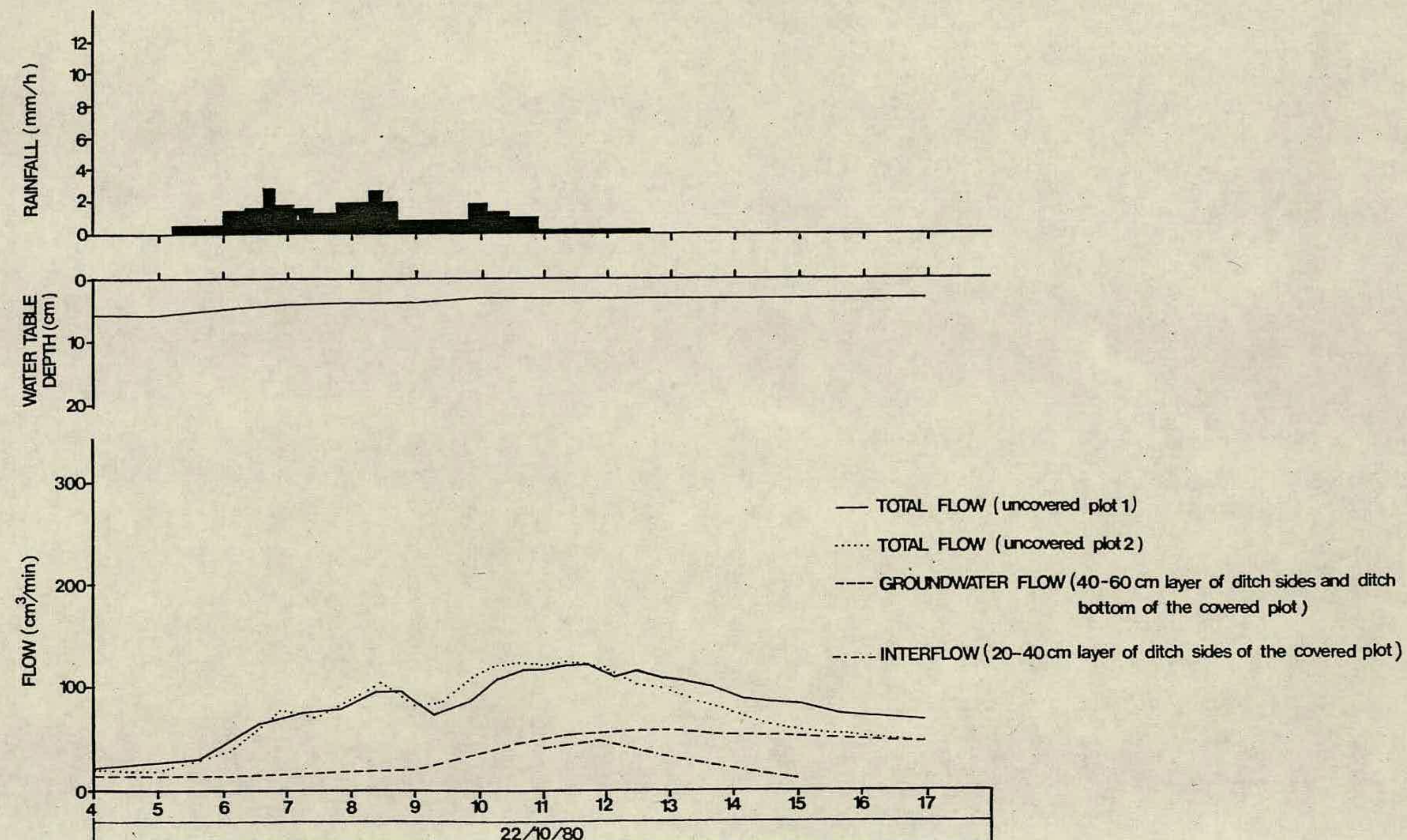


Figure 24 : Rainfall, water table changes and combined hydrographs from the runoff plots on October 22, 1980.

type of peat than the rest of the layer. This quick interflow response seems thus to be "channelled" and conducted by localized areas of more permeable peat. On account of this, interflow is certainly very variable along any ditch section and between different ditch sections.

It is also important to note that during all the period of record flow emerging from the top peat layer (0 - 20 cm below surface) of the strips was insignificant and could always be accounted for by the fact that the upper gutters of the covered plot were pushed 20 cm into the ditch sides and thus intercept the vertical movement of some infiltrating water. These results also mean that any possible contribution of overland flow from the strips was not significant during all the period of record.

Summarizing the previous conclusions it can be generally stated that:

1. The major component of any storm event consists of saturation overland flow originated by direct rainfall into the ditches.
2. When flow from the strips occurs, the most common type of flow is groundwater flow slowly released from the lower peat layers.
3. When the water table under the centre of the strips is near the top of the peat profile, and thus located within the upper permeable layer, a quick response of interflow emerges from the 20 - 40 cm deep layer of the ditch slopes.

These conclusions are supported by Figures 22, 23 and 24 but they are also in agreement with the total number of floods recorded from the runoff plots. Although many other examples could be shown, it did not seem reasonable to add more material that would only repeat and corroborate the information already given.

The general conclusions concerning the relative importance of different flow components can also be analysed on a longer term basis using the continuous run of flow records from the plots for the period 29 April - 30 September 1980. Appendix 6 shows weekly data on flow component amounts recorded from the plots. Table 11 summarizes these data and presents the flow component amounts recorded during the entire period. The relative proportions of these flow components will certainly vary at different times of the year, depending on the prevailing soil moisture conditions.

The movement of water through the deep peat layers towards the ditches can be visualized using flow nets drawn from the piezometer nests (see 2.3.3). Figure 25 shows the flow net pattern on November 6th 1979, which typifies all others drawn for this bog during recharging situations. Water moves vertically downwards in the centre of the strips and then follows a curving path towards the ditches. Some water enters the ditches vertically from below. This general groundwater flow pattern agrees well with a similar study presented by Boelter (1972b) who analysed the flow net around an open

Period	Flow from strips (covered plot) (litres)		Total Flow (litres)		Flow from ditches (estimated) (litres)	
	Groundwater flow (1)	Interflow (2)	Uncovered Plot 1 (3)	Uncovered Plot 2 (4)	Uncovered Plot 1 (3)-((1)+(2))	Uncovered Plot 2 (4)-((1)+(2))
29/4/80 30/9/80	405.6	34.5	1047.7	1093.3	607.6	653.2
	440.1					

TABLE 11 : Flow component amounts recorded from the runoff plots during the 1980 growing season.

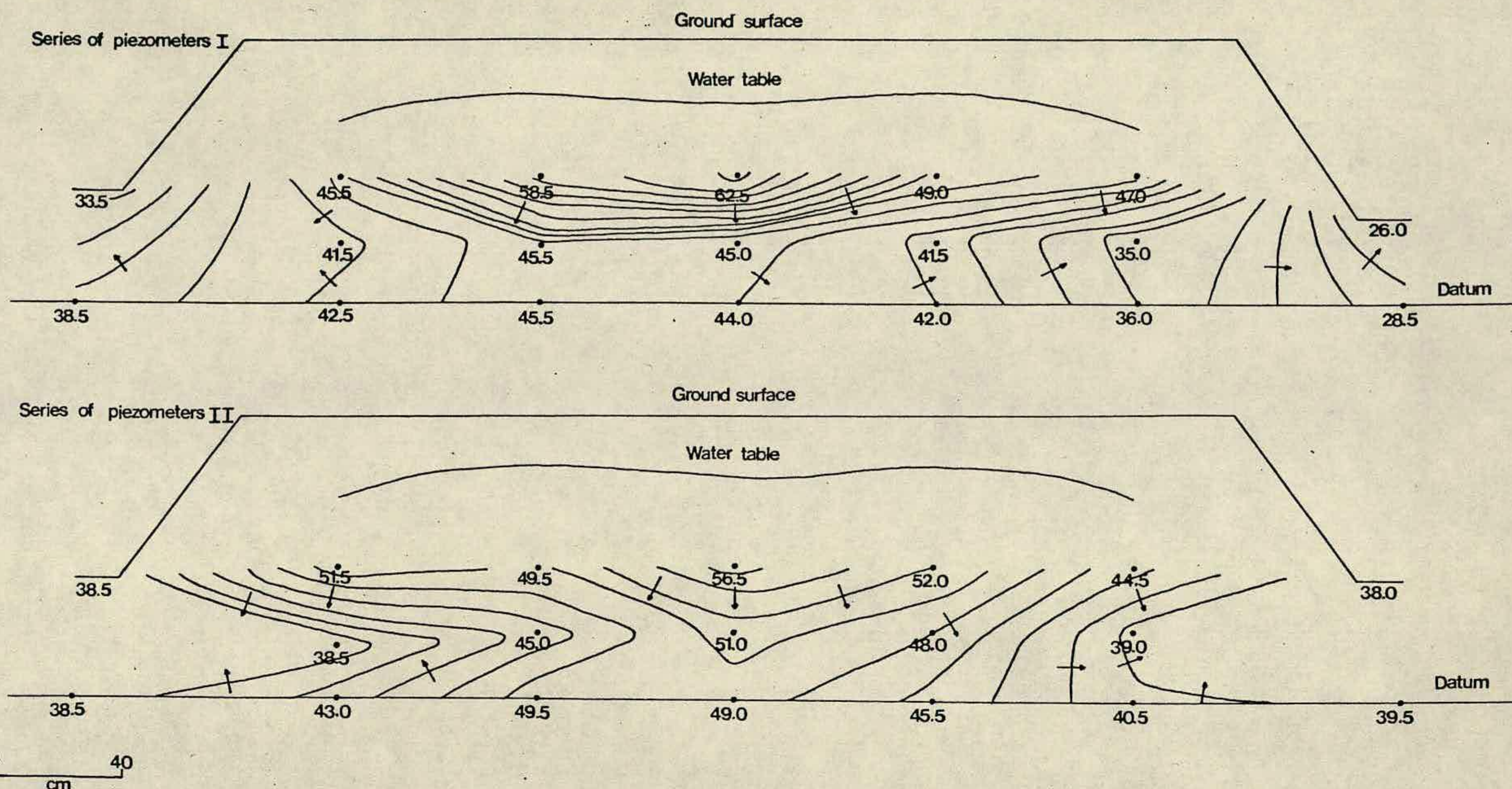


Figure 25 : Flow net showing lines of equal hydraulic head, between neighbouring ditches, on November 6, 1979. Numbers indicate the hydraulic head in cm. Intervals between lines represent hydraulic head differences of 2 cm. Water flows perpendicular to the equipotential lines as indicated by the arrows.

ditch also using nests of piezometers. Figure 25 also shows that groundwater flow patterns may vary between different strip cross sections. This indicates the possible existence of variability in the spatial distribution of groundwater flow.

The groundwater flow rate into the ditches was also calculated using piezometer data as outlined by Reeve and Jensen (1949) (see 2.3.3). As was mentioned earlier (see 2.3.3) the piezometer nests were not dense enough to allow accurate measurement of some parameters needed for the application of the method. Furthermore the piezometers did not cover the upper layer of the profile. As a consequence the application of the method was liable to some subjective judgement. In spite of this groundwater flow rates were calculated for several days. The Reeve and Jensen (1949) method yielded flow rates significantly lower than those measured at the bottom layer of the covered plot. Similar significant underestimation of groundwater flow rates by this method has also been experienced by Boelter (1972b).

3.3.3 Generalization of the Results on Flow Components to the Other Areas of the Site

Data from the runoff plots and from the piezometer nests seem to characterize reasonably well the flow processes occurring in areas in which these instruments were located, i.e. areas drained by 60 cm deep ditches. However, it is also important to know whether areas drained by the other types of ditches (see 1.2) behave in a similar way. Although no detailed work was done in other parts of the experimental site, some small hydrological experiments were carried out that at least give some indication on whether or not different areas are behaving similarly. For example, water table depth was measured in the centre of strips between 90 cm deep ditches (see 2.1.3) and flow rates were measured at the outlets of two 90 cm deep ditches and two 60 cm deep ditches (see 2.3.4).

It has been shown that the relative importance of different flow components depends on the prevailing soil moisture conditions, and thus on prevailing water table levels. During the period February - November 1980, water table depths on the centre of strips between 60 cm ditches could be compared with water table depths on the centre of strips between 90 cm ditches (Figure 26). The good relationship found indicates that, in broad terms, the water table of areas drained by 90 cm deep ditches is approximately 5 cm deeper than in areas drained by 60 cm deep ditches. No data are available on water table depths in the centre of strips between the wide 60 cm deep ditches. The results in Figure 26 also indicate that the water table of areas drained by 90 cm ditches varies in harmony with the water table of areas drained by 60 cm ditches. It seems thus reasonable to assume that the water table depth on areas drained by 60 cm ditches is a good index of the water table levels of

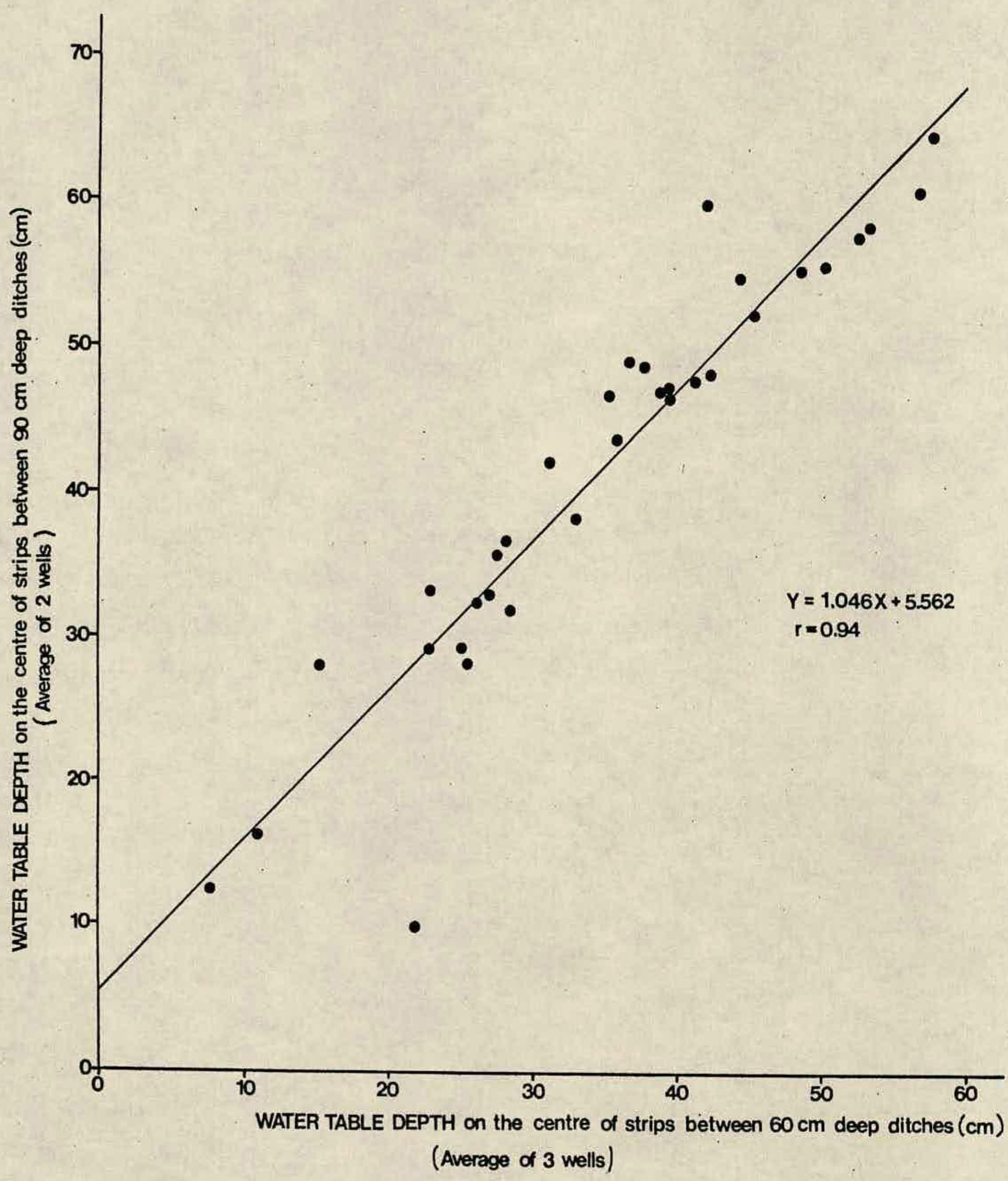


Figure 26 : Relationship between the water table depths under the centre of strips between 90 cm ditches and those under strips between 60 cm ditches.

other areas of the experimental site.

Flow rates from 60 cm and 90 cm deep ditches were also measured independently. Figure 27 shows the relationship between flow rates measured from these two types of areas. In spite of the relatively small number of points, the relationship found indicates that outflow from 90 cm ditches does not differ significantly from the outflow of areas drained by 60 cm ditches.

To see whether the conclusions drawn from the flow measuring plots can be extrapolated to other parts of the experimental site, comparisons can also be made between total hydrographs measured at the runoff plots and the corresponding hydrographs recorded at the site outlet as in Figure 28. Flow rates from these different sources are only comparable when expressed in equivalent millimetres per unit time. The hydrograph measured at the V-notch has a similar shape and a similar range of values when compared with the hydrograph recorded at the uncovered runoff plots. However, the V-notch hydrograph is slightly smoother, probably on account of the storage effects of the channel network. The example shown in Figure 28 typifies all other similar comparisons done for other events.

These results tend to indicate that flow generation processes probably do not vary significantly between areas drained by different types of ditches.

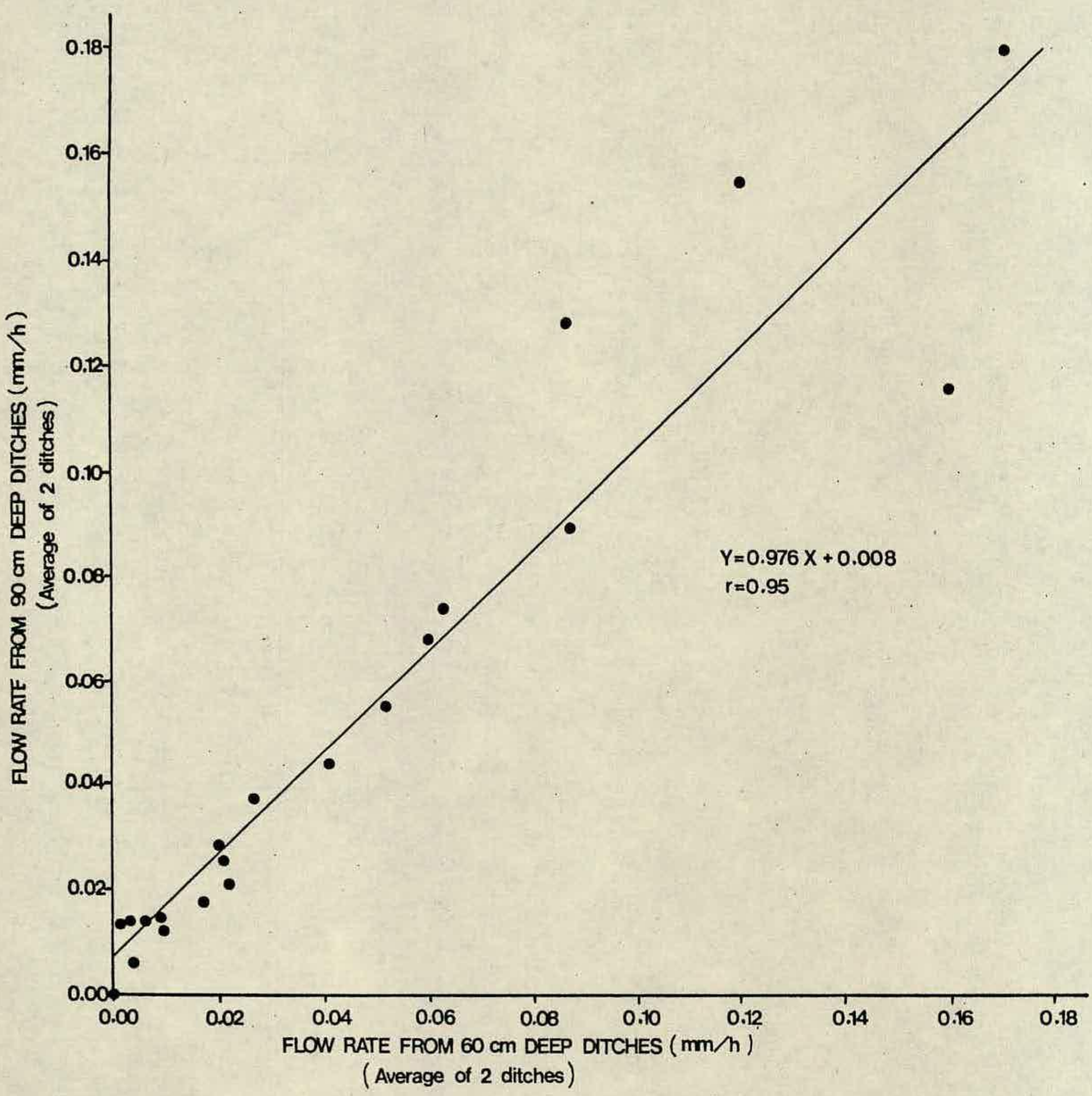


Figure 27 : Relationship between flow rates measured from 90 cm and 60 cm deep ditches.

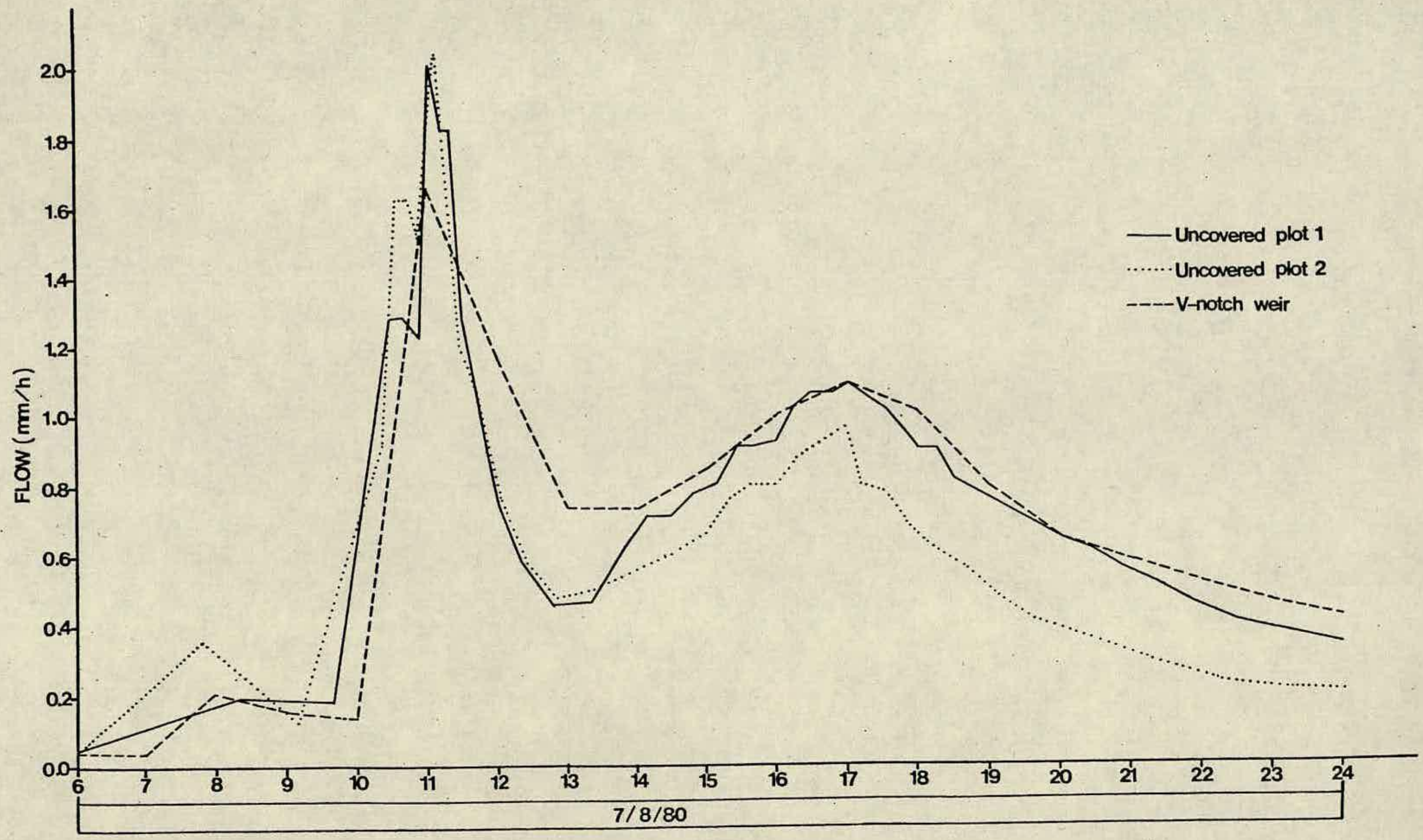


Figure 28 : Comparison between discharge hydrographs measured at the uncovered runoff plots and at the V-notch weir on August 7, 1980.

3.3.4 Discussion

The fact that a network of open ditches speeds up the hydrological response of recently drained peatlands has been emphasized by Ahti (1980), Binns (1979), Mustonen and Seuna (1975), Seuna (1974) and Howe et al (1966). However, in these works very few data were presented to explain the hydrological behaviour of the ditch areas. The results of the present work show clearly that saturation overland flow originated by direct rainfall into the ditches is the major component of any flood event. Conway and Millar (1960) found that hydrographs from peatlands drained by a network of open ditches were much more flashy than corresponding hydrographs of undrained peatlands. According to the results of the present work this is probably due to the influence of the large area of open ditch which is created after this type of drainage.

The flow components emerging from the strips are generated in a way that conflicts with some of the hypotheses originally thought to be most probable. It has been shown (see 2.3.1) that when there are breaks in the vertical permeability profile of the soil temporary perched saturation zones can be created above them and then so called throughflow is generated (Weyman, 1973). As it was known (Cuttle, pers. comm.) that the peat of the experimental area was composed of two layers of very different permeabilities, it was thought that this type of throughflow would probably occur there. Furthermore it has also been shown that infiltration capacity equals the saturated hydraulic conductivity when the soil is near saturation (Childs, 1972; Rose, 1966). As a result this type of throughflow was mainly expected to occur during periods when rainfall intensity exceeded the saturated hydraulic conductivity of the deeper peat layer. The saturated hydraulic conductivity of the deeper peat layer is approximately of 1 cm/day (Cuttle, pers. comm.). The possible occurrence of throughflow on peatlands was theoretically emphasized by Goode et al (1977).

However, and contrary to what was expected, vertical infiltration of water into the strips between ditches apparently was never restricted by the boundary of the two peat layers. A possible example of this is the double peaked hydrograph shown in Figure 23. During the part of the storm with higher rainfall intensities, which was probably the more critical for the generation of throughflow, no flow was generated in the top peat layers. Quick responses from the more permeable layers were only observed during the second part of the storm, when the water table was very high, in spite of the lower rainfall rates of this last period. However, this interpretation is certainly not conclusive as it is also known that infiltration rates vary in time, being higher during the first part of the storms when the soil is drier (Childs, 1972). Nevertheless, for all the recorded events, the existence or non-existence of quick responses from the strips seemed only to be related with the preceding water table levels and not with rainfall intensities. When the water table was high, even very small rainfall events generated some interflow. If the initial water table level was low, and provided that it was not raised to the top layers during the event, interflow did not occur even for relatively heavy events. On the other hand, if it is assumed that perched saturation zones can occur in the upper peat layer during heavy storms, water level rises inside the wells will have no relation whatsoever with the main water table level, as some water will enter the well quickly through the upper permeable layers. If this was to be true, studies of water table responses to rainfall using perforated wells, with a low initial water table, would probably be meaningless. Such water table responses have however been monitored in peatlands by different authors (i.e. Boelter and Verry, 1977; Vorob'ev, 1963; Heikurainen, 1963). It is then obvious that the assumption that there is no restriction on the infiltration of water along a peat profile is implicit in a fair number of previous works on peat hydrology.

According to Boelter (1972b) when the water table is located within the permeable surface horizons of the peat, flow rates from the peat into the ditches are high. He also found that when the water table dropped below this permeable layer, the rate of flow was greatly reduced. These conclusions agree well with the results of the present study. However, Boelter's findings were based mainly on situations when the water table was dropping and not when the water table was rising in response to rainfall.

With the information available, it is difficult to explain the reasons why infiltration is not restricted across the boundary of the two peat layers. One possible explanation for this fact is the spatial heterogeneity of the peat. Hydraulic conductivity may vary widely from point to point and thus the assumed value of 1 cm/day for the deeper peat layer may underestimate the real average value.

Another difficulty was experienced when soil physics principles were applied to estimate groundwater flow rates from piezometer data. It has already been mentioned that the piezometer nests were not dense enough for detailed analysis and thus the application of the Reeve and Jensen (1949) method was liable to some subjective judgement. Furthermore, this method is based on the Darcy's law (see 2.3.3) and it has been shown that this law is not applicable for decomposed peat layers (Rycroft et al, 1975b, Ingram et al, 1974).

Some future work is obviously needed to explain these unsolved problems. Detailed work on soil water movement, explained on a soil physics basis, was not, however, one of the main objectives of the present study.

It was mentioned in section 1.1 that the temporal distribution of outflow from recently drained peatlands for forestry purposes has been found to be different from the better known outflow patterns of undrained peatlands and peatlands drained for agricultural purposes. The conclusion of the present study, according to which saturation overland flow generated from ditch areas is the major component of any storm event, probably helps explain some of the differences noted earlier. In fact the existence of ditch areas is a specific attribute of peatland drained for forestry and similar areas do not exist, at least with the same density, in peatlands used for agricultural purposes.

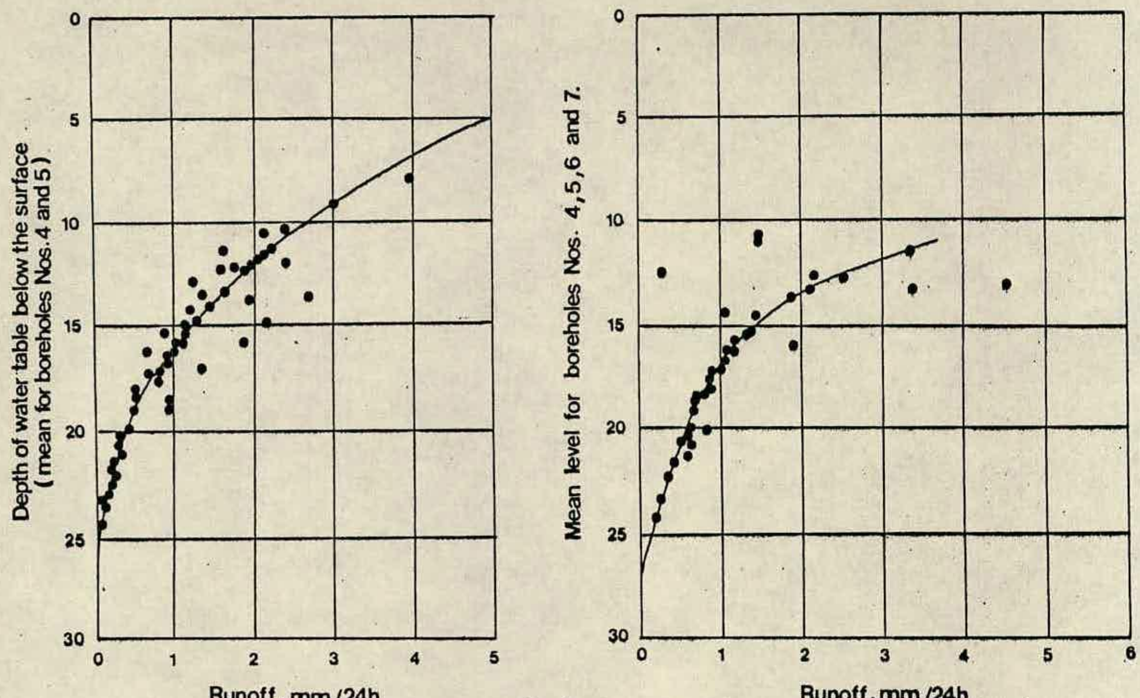
The results presented in this section seem to be based on a sound experimental basis. One of the main criticisms that can be made about the data from the runoff plots is their possible lack of representativeness. However, the reasonably good agreement between the hydrographs of the different plots as well as the good agreement between the results of the plots and the V-notch weir data, indicate that this is certainly not a major problem. It is possible that the gutters, dams, and other physical objects used in the construction of the plots (see 2.3.2) may be interfering with the natural characteristics of the flow. However, as flow components were collected from natural ditch sides these interferences were certainly kept to a minimum (Atkinson, 1978). Quantitative extrapolations of the plot results are certainly not valid when interflow occurs. In fact, it has been shown that this flow component has a high degree of spatial variation. As a consequence the assumption that midway lines between parallel ditches provide streamline boundaries (see 2.3.2) is certainly not valid for interflow. However, this is not a major problem in the long-term analysis of flow amounts from the plots as interflow only occurs during very localized and not very frequent periods. Overall the plots gave very relevant data and they certainly constitute the most successful experimental work carried out during the present study.

3.4 Relationship between Water Table Depth and Flow Rates.

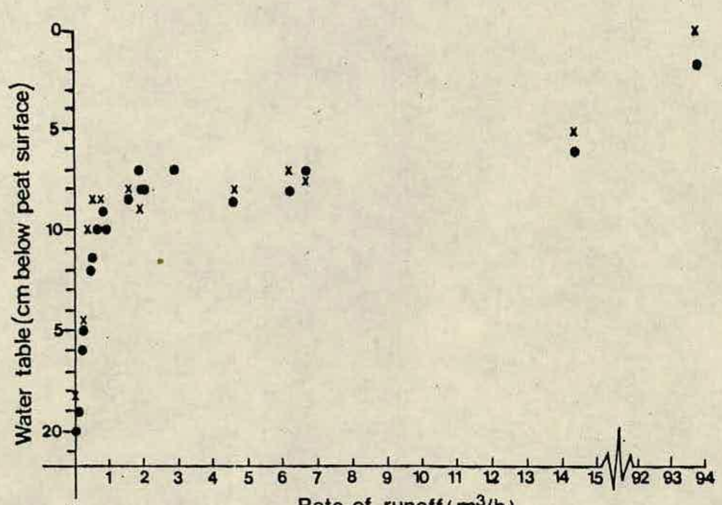
3.4.1 Introduction

It is well known that outflow from undrained bogs is progressively reduced as the water table drops (Goode et al, 1977). The relationship between water table depth and outflow from undrained bogs has been particularly studied by Romanov (1968b) and Chapman (1965) (Figure 29). In the two examples extracted from Romanov (1968b) (Figure 29a), outflow from the bog completely stopped when the water table dropped below 25 cm. In the example extracted from Chapman (1965) (Figure 29b), outflow from the bog stopped when the water table dropped below 20 cm. Results presented by Bay (1968) accord with those of Romanov (1968b) and Chapman (1965). According to Ivanov (1957), cited by Goode et al (1977), the water level at which outflow ceases is always lower than the water level at which flow recommences. This difference has ranged from 1 to 10 cm in different studies. When water table drops below the level at which outflow stops, further lowering is accomplished only by evapotranspiration (Goode et al, 1977; Bay, 1968).

The relationships between water table depth and outflow were termed runoff curves by Romanov (1968b) and were used by him to calculate outflow from undrained bogs solely using water table data.



(a)



(b)

Figure 29 : Relationships between water table depth and runoff found by previous authors.

(a) Runoff curves relative to the water table. Central part of Lammin-Suo Massif at the left and convex part at the right (after Romanov, 1968b).

(b) The relationship between the height of water table and the rate of runoff for catchment area 2. x, water table at site 1; •, water table at site 2 (after Chapman, 1965).

To derive similar relationships between outflow and water table depth for the present site, some already known facts must be taken into consideration:

1. It is known (see 3.3.2) that during rainy periods, saturation overland flow generated on the ditch areas is a major component of the total outflow. This being so, total outflow rates during such periods will certainly be more dependent on rainfall intensity than on the water table level.
2. During rainless periods, total outflow is only generated by flow coming from the strips, as overland flow from the ditches stops quickly after rainfall ceases.

Given this situation it seems reasonable to assume that a good relationship would exist between water table level and the flow rates from the strips of drained areas, and thus between water table level and total outflow during rainless periods.

3.4.2 Results and Discussion

Following the above line of reasoning, the relationship between total outflow and water table depth was studied during rainless periods (Figures 30 and 31). Flow rates were calculated from the V-notch weir records and water table depth was calculated as the average of the readings of three wells centrally located on strips between 60 cm ditches.

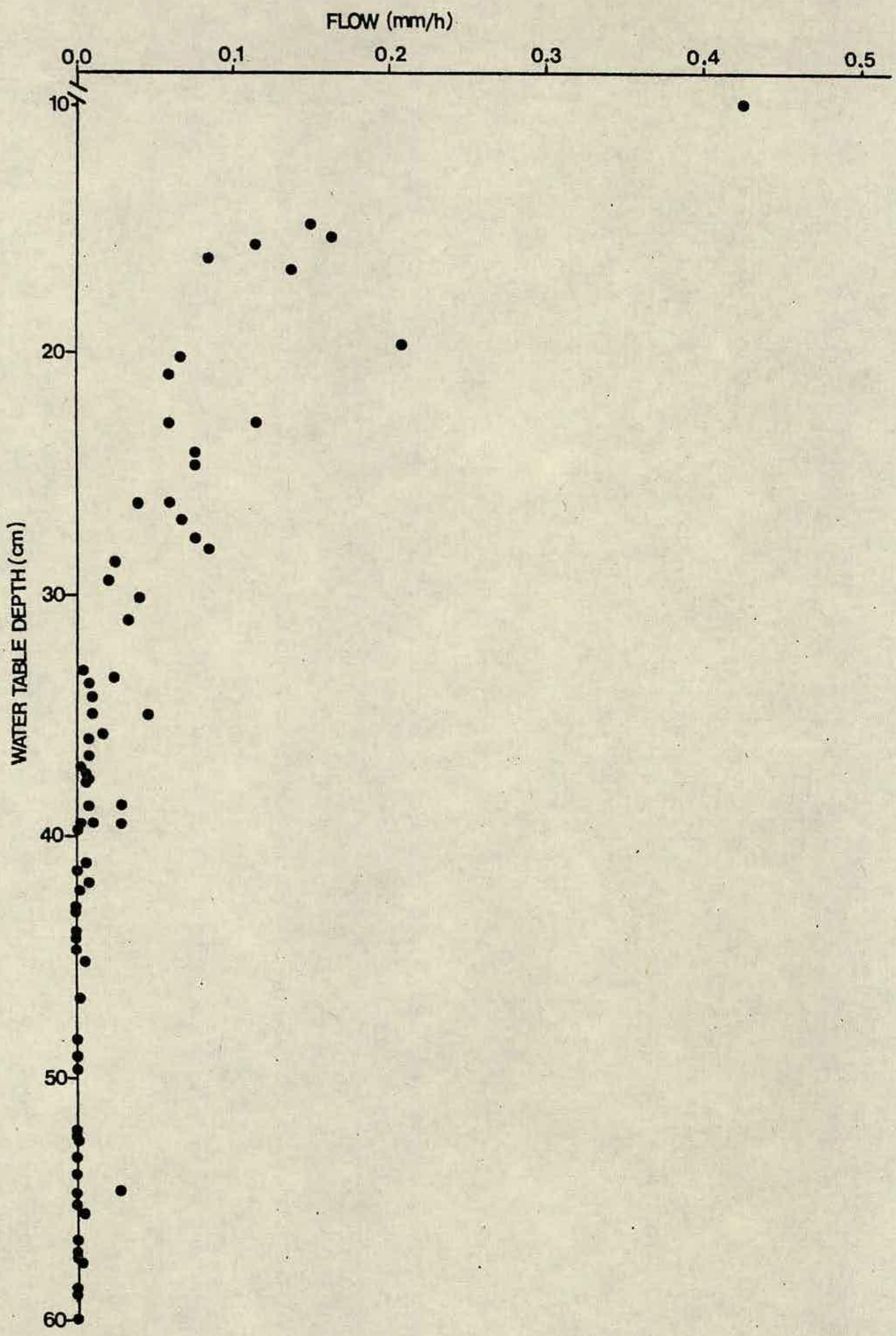


Figure 30 : Relationship between flow rates and water table depth during rainless periods.

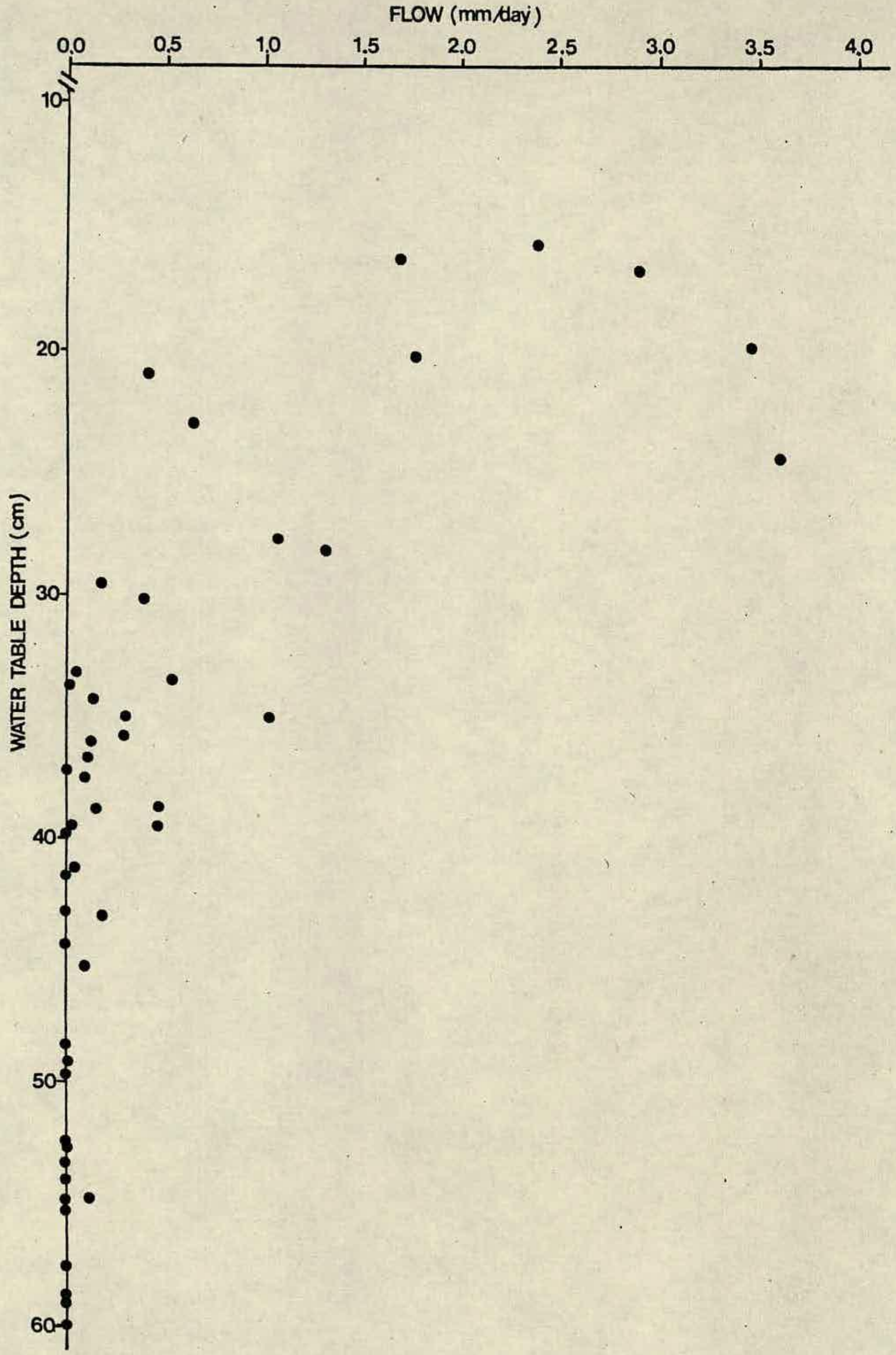


Figure 31 : Relationship between daily flows and water table depth during rainless periods.

In Figure 30 flow rates were measured at 10 a.m., the time at which well readings were also taken, and were plotted against water table depth. The data in Figure 30 were only plotted for days during which 10 a.m. was preceded and followed by rainless periods of at least 6 hours. Figure 31 shows a similar relationship between daily flows and water table depth. Again values were only plotted for rainless days preceded and followed by rainless periods of 6 hours.

Figures 30 and 31 show that total outflow during rainless periods (i.e. flow from strips), has a reasonable relationship with water table depth. Flow from the strips stops when the water table drops below 40 - 45 cm. As was shown (see 3.3.3) water table depth on areas drained by 60 cm ditches is a good index of the water table levels of other areas of the experimental site too. This being so, if water table levels of areas drained by 90 cm deep ditches or simple average values for the whole area were used instead in Figures 30 and 31, similarly shaped relationships would certainly be found. As it is known that the water table level of areas drained by 90 cm ditches is on average 5 cm lower than on areas drained by 60 cm ditches (see 3.3.3), the data in Figures 30 and 31 also indicate that flow from the strips stops when the water table on areas drained by 90 cm ditches drops below 45 - 50 cm.

As Romanov (1968b) did for undrained areas, the relationships shown in Figures 30 and 31 could probably be used to compute outflow rates from the areas of strips, solely from water table data. Knowledge of these relationships together with the fact that during rainy periods actual ditch flow equals impermeable ditch flow (see 3.2.2), would eventually allow computation of the total outflow from the area solely from water table and rainfall data. However, this procedure would certainly yield only rough estimates of total outflow. In fact, the scatter of data shown in Figures 30 and 31 means that important errors would be involved in the estimation of flow from the strips. Furthermore, when the water table is located within the upper permeable layer of the peat, a quick response of interflow emerges from the strips (see 3.3.2). On account of its high permeability the upper peat layer responds quickly to any additional rainfall input when the initial water table level was already high. On the other hand, the specific yield of this layer is also very high (see 3.2.2), which means that water table level variations per unit input or output of water are small within this layer. This means that,given high water tables,interflow rates are certainly more dependent on rainfall intensity than on the water table level. For high water tables, the relationship between flow from strips and water table will tend to a horizontal line which means that under these conditions flow rates are almost independent of the water table levels. This tendency is clearly shown in Figure 31.

For the reasons outlined the relationships shown in Figures 30 and 31 were not used to predict flow rates from the strips. Furthermore the number of points available, particularly for high water tables, was not big enough to define the real tendency of the relationship with any confidence.

Some other conclusions can also be derived from Figures 30 and 31 which apparently slightly conflict with some of the previous results. For instance, according to Figures 30 and 31 outflow from the strips is substantially increased when the water table is located within the top 20 cm of the peat profile. This would also mean that the top permeable layer of the peat is approximately 20 cm deep. On the other hand, the results from the runoff plots indicate that quick responses from the strips occur when the water table is located, approximately, within the top 5 cm of the soil. Furthermore, according to specific yield calculations (see 3.2.2), specific yield is substantially increased only in the top 10 cm of the soil. As it is known that the specific yield is very much related with soil macroporosity (Vorob'ev, 1963), this will also mean that the more permeable peat layer stops approximately 10 cm below the surface. It can be seen then that different methods can yield slightly different estimates of the possible depth of the upper and more permeable peat layer. However, these differences should be expected as it is known (Cuttle, pers. comm.) that the depth of this upper layer is variable and that different wells, located at different points, were used to derive the different results.

3.5 Modelling the Hydrological Response of the Experimental Area

3.5.1 Introduction

As was mentioned earlier (see 1.1) much of published quantitative information on peat hydrology suffers from the disadvantage of being empirically derived and thus cannot be interpreted in terms of general principles (Dooge, 1975). Several authors have emphasized that an increase in the use of conceptual models in peat hydrology would probably improve knowledge of the hydrological behaviour of such areas (Dooge, 1975; Zubets and Murashko, 1975). As most of the experimental research of this work dealt with the study of hydrologic processes, considerable information is available to support the construction of a conceptual model.

The general experimental conclusions thought basically important for modelling purposes can be summarized as follows (see 3.3.4):

1. The areas of ditches and the areas of strips between ditches differ significantly on their hydrological behaviour.
2. Infiltration on the strips between the ditches is not restricted across the boundary between the upper and lower peat layers and quick interflow responses only occur when the water table is located within the upper permeable layer.

3. Saturation overland flow generated by direct rainfall into the ditches is the major component of stormflow. During wet periods the ditch areas work as impermeable areas.

It was felt that, if these conclusions are correct, a model taking them into account would probably predict with some accuracy the response of the experimental area to rainfall. These conclusions are summarized in diagrammatic form in Figure 32 which can also be regarded as the background conceptual basis for the modelling exercise to be presented. Ideally a conceptual model should explain all the physical processes occurring in the study area. However, the conclusions listed do not completely explain all the physical processes occurring at the site. Because of this, the model to be built will obviously only be partially representative of the physical system. According to Fleming (1975) and Douglas (1974), a model always involves some simplification and the use of empiric relationships is still necessary, since the subject has not yet produced complete analytical relationships between hydrologic processes and may never do so. Nevertheless, if the model is a reasonable representation of the physical system its output will approximate closely to the real output (Douglas, 1974). This being so, a conceptual model can be an indirect way of checking if the concepts on which it is based are or are not correct. The modelling exercise to be presented in the following sections has the specific objective of being an

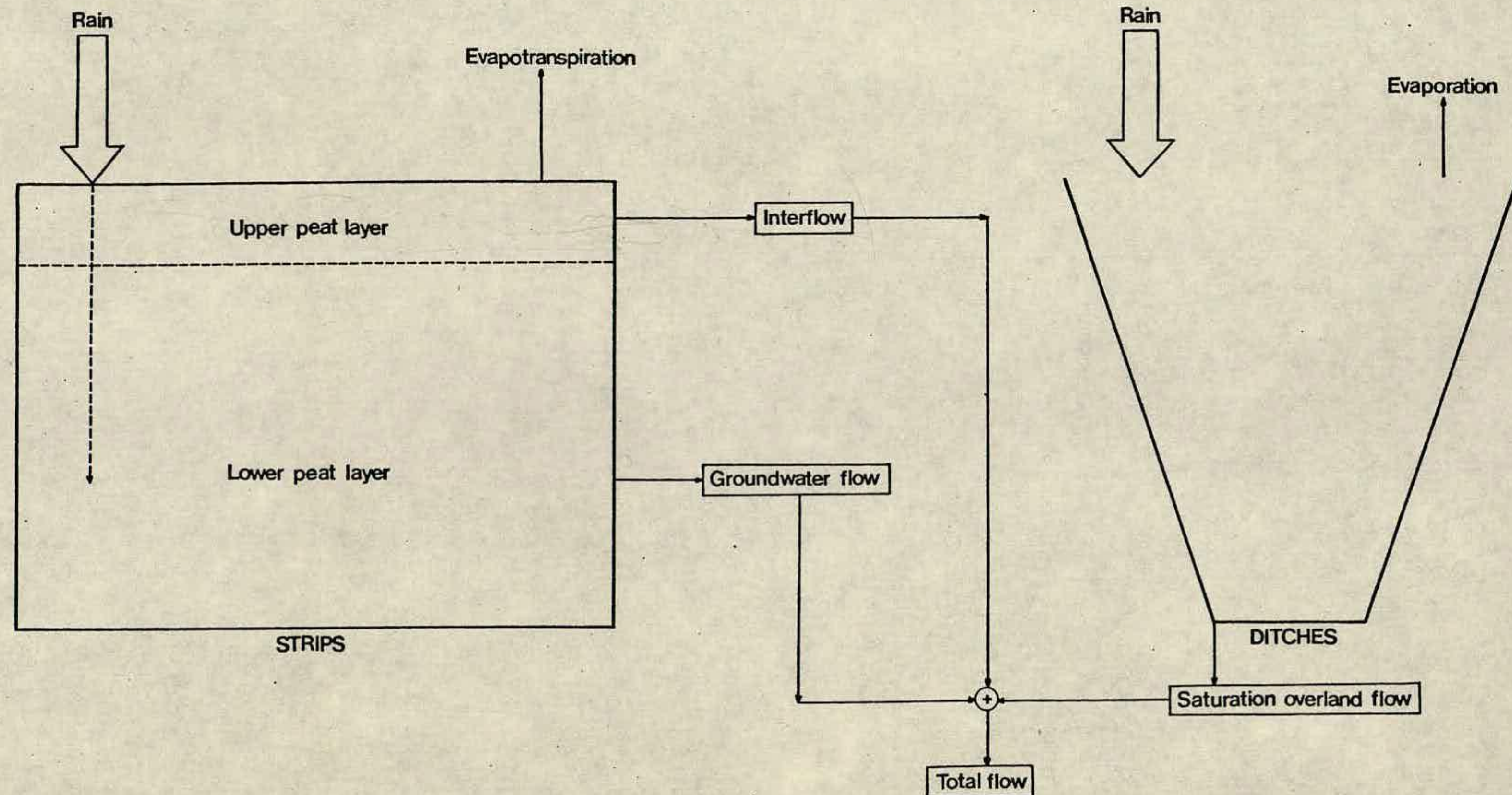


Figure 32 : Diagram summarizing the main experimental findings on runoff processes. The term interflow is used according to the definition given on page 152. It is also important to note that the boundary between the upper and lower peat layers does not restrict the vertical infiltration of water.

additional and integrated way of checking the validity of the experimental conclusions drawn in the preceding sections.

3.5.2 Description of the Model

As was mentioned in sections 3.2 and 3.3, all the results showed that the strips and the ditches differ significantly in their hydrological behaviour. In fact it was shown that evapotranspiration rates as well as flow processes are quite different in these two component parts of the experimental area. For simulation purposes it is then logical to consider the site as divided into these two more or less independent parts. In previous sections the ditch areas were analysed as a whole and no distinction was made between the hydrological behaviour of ditch slopes and ditch bottoms. However, for modelling purposes, and to try to make the model structure more physically based it was found convenient to make such a distinction. Hence the model can be summarized briefly as consisting of three different components working in parallel: the strip component, the ditch slope component and the ditch bottom component. This model thus defines 3 main regions which are considered as homogeneous for the purpose of analysis. A model supported on this kind of region definition is usually referred as a lumped model (Fleming, 1975).

The three basic input data files for the model consist of rainfall, evapotranspiration and observed flows.

The rainfall input consists of two-hourly rainfall amounts. These were read directly from the charts of the tilting-siphon raingauge recorder (see 2.1.2). As was mentioned this instrument gives rainfall readings that are in close agreement with the areal rainfall computed from the non-recording raingauges (see 2.1.2). This good agreement indicated that direct readings from the recording raingauge were good enough to provide the two-hourly rainfall input for the model. Time-steps of two hours were chosen as this was the minimum interval for which it was possible to read the rainfall charts with accuracy.

The input data file on evapotranspiration consists of daily potential evapotranspiration computed by the Penman formula for the nearest meteorological station, which is located at Penicuik. Evapotranspiration data from this station were only available on a weekly basis. Thus the daily values of the input data file are in fact mean daily values for each week.

The input data file on observed flows consists of two-hourly flows computed from the charts of the water level recorder at the V-notch weir.

Rainfall inputs are routed through the three components of the model and the different flow outputs of each component are finally integrated to produce a total flow output. Computed flows are then compared with observed flows by an error function.

All the computations of the model are done on a two-hourly basis. The output of the model consists of two-hourly as well as daily flow estimates. The computer program was written in a local version of Fortran, Edinburgh Fortran, and runs over periods of fifty days, i.e. 600 two-hourly intervals. The program has two main loops: one for the total period of 50 days and an internal loop for the twelve two-hourly time-steps for each day. It was only possible to define three Autumn periods of 50 days during which completely reliable rainfall data were available. The pen of the raingauge recorder occasionally did not write and this created some problems in the selection of periods with reliable data. If longer rainfall files had been selected this problem would have been a very real one.

The functioning of the different components of the model is described in detail in the following sections.

3.5.2.1 The Strip Component

The strip component of the model attempts to simulate the hydrological behaviour of the strips between ditches. The total area occupied by strips is a model parameter (AID) and has a value of 1.757 ha.

The only physical input into the strips consists of rainfall (R) and the outputs are evapotranspiration (ARE), groundwater flow (QG), interflow (QI) and surface flow (R1)*. As was described, rainfall and potential evapotranspiration are fed into the computer program as input files.

It was seen in section 3.2.2 that actual evapotranspiration from the strips equals Penman potential evapotranspiration. As potential evapotranspiration values are fed in the program as average daily values (RE), it is necessary to compute average two-hourly values to allow the calculations to be performed on a two-hourly basis. This was done in the following way:

If $5 \leq \text{ICOL} \leq 9$ and $\text{R(ICOL)} = 0$

then $\text{ARE} = \text{RE}/5$. (23)

In all other cases ARE = 0. In the previous calculations ARE is the two-hourly evapotranspiration, RE is the daily evapotranspiration and ICOL is the two-hourly time-step number for that specific day of calculation. These computations assume that the evapotranspiration is only effective from 8 a.m. (ICOL = 5) until 6 p.m. (ICOL = 9) and when there is no rainfall.

The strip component is considered as divided into two storage layers: the subsurface storage and the groundwater storage. These two storages are intended to represent the upper permeable peat layer and the lower decomposed peat layer. According to the results shown in 3.3.2, infiltration is assumed not to be restricted across the boundary between the two layers.

Groundwater storage (SG) is updated during each two-

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* For convenience, a glossary of the symbols used in the model is given in Appendix 9.

hourly time-step in the following way:

SG(ICOL)=SG(ICOL-1)-QG(ICOL)+R(ICOL)+SI(ICOL-1)-ARE (24)

in which SG is the groundwater storage, QG is the groundwater flow, R is the rainfall, SI is the subsurface storage and ARE the evapotranspiration. All terms in equation (24) are expressed in mm. The form of equation (24) means that for each time-step rainfall as well as any previous subsurface storage is allowed to percolate freely into the groundwater storage. This storage loses water by evapotranspiration and groundwater discharge. The groundwater flow (QG) has to be previously known to allow computation of equation (24). The groundwater storage is considered as a linear storage and groundwater flow is computed by the equation:

QG(ICOL) = RG x SG(ICOL-1) (25)

in which RG is the storage constant. Groundwater flow is assumed to be proportional to the groundwater storage value of the previous time-step. Hence a lag of 2 hours is introduced into the groundwater storage response. This seems a reasonable procedure as it is known that the lower peat layer responds slowly to rainfall inputs (see 3.3). According to Leavesley(1973) RG can be calculated by the following formula:

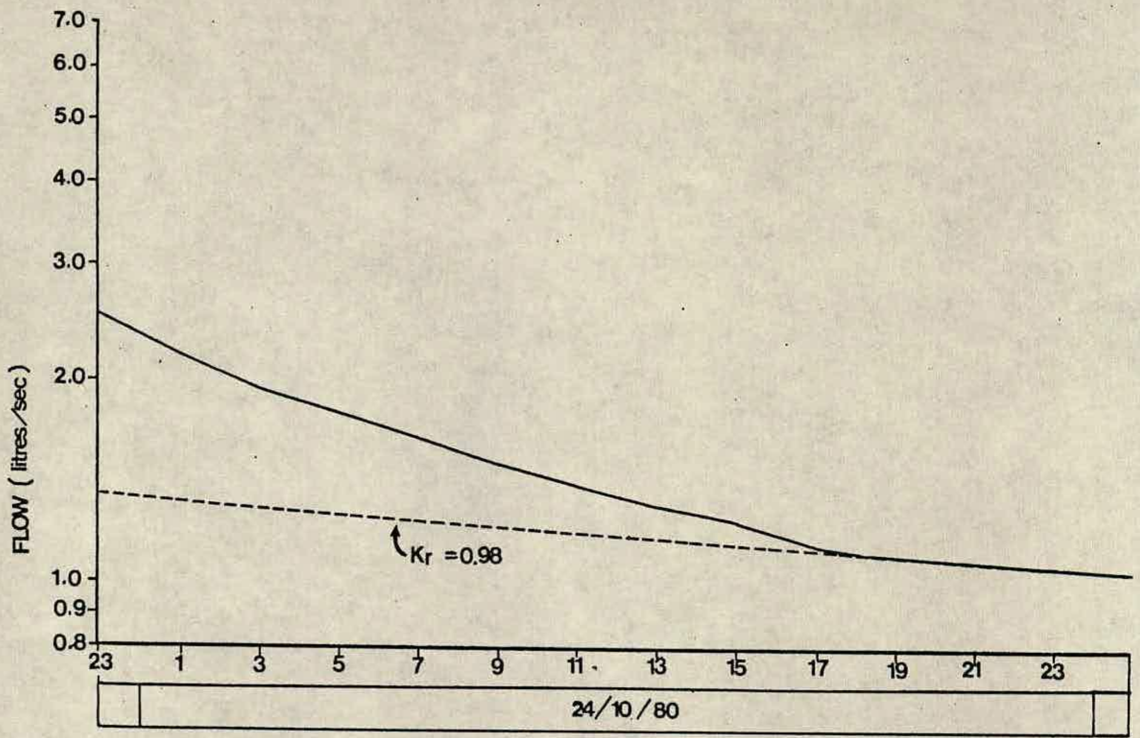
RG = (1 - Kr) (26)

in which Kr is the recession constant of groundwater flow. The two-hourly recession constant was estimated analysing several semilogarithmic graphs of the recession limbs of V-notch hydrographs by the method described by Schulz

(1973). Figure 33 shows two such analyses. In all the events analysed Kr had values very close to 0.98. Hence, according to equation (26), RG has a value of 0.02. RG is a model parameter.

During very dry periods SG, computed by equation (24), can have negative values. Such a value means that groundwater storage is below the minimum level needed to generate groundwater flow. Under these conditions QG is assigned a zero value since otherwise equation (25) would yield negative QG values which does not make sense. The groundwater storage has a maximum capacity (GMA) when the lower peat layer is completely saturated. According to the results of section 3.4 groundwater flow stops when the water table depth is about 45 cm. On the other hand it was also shown that the upper limit of this same layer is approximately 10 cm below the ground surface. This being so, only water table fluctuations within the top 35 cm of the lower decomposed peat layer are significant for groundwater flow generation. After some small adjustments, by trial and error within a limited range of feasible values, a value of 18 mm was assigned to the model parameter GMA. It was seen in section 3.2.2 that the specific yield of the lower peat layer ranged from 0.05 to 0.10. Assuming an average specific yield value of 0.06, a storage variation of 18 mm corresponds to a water table variation of 1.8/0.06 = 30 cm. Thus the assigned value for GMA is in reasonable agreement with the experimental findings.

It was previously mentioned that when the water table



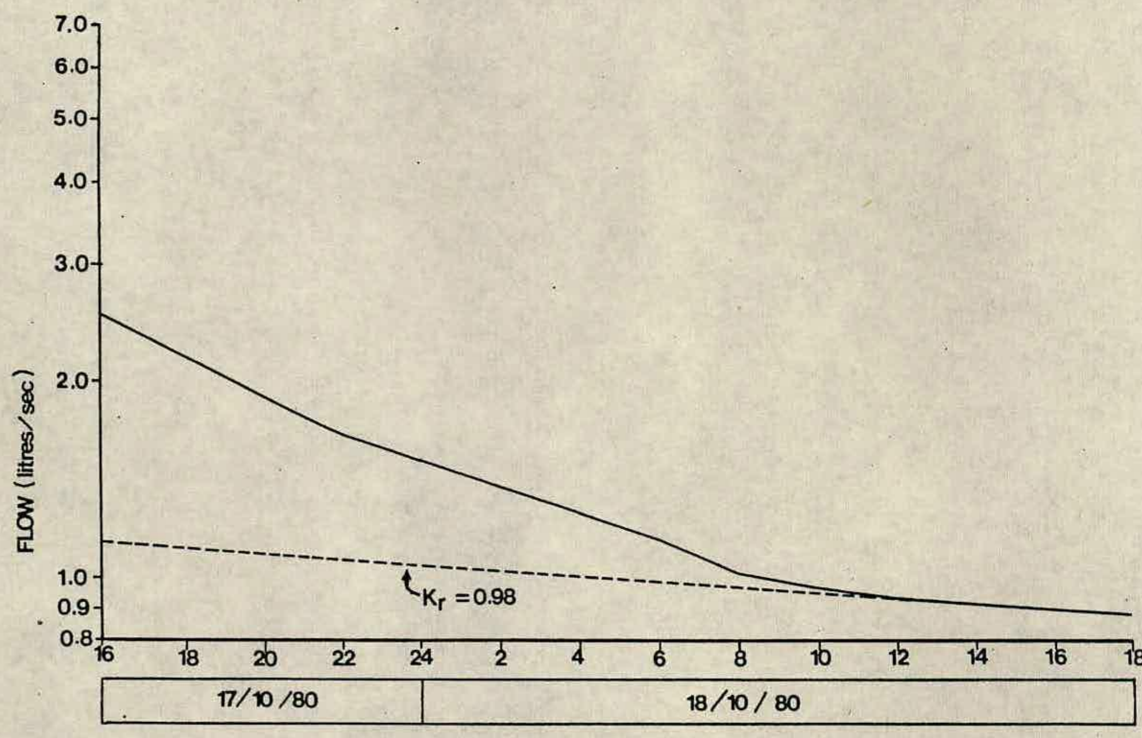


Figure 33: Analysis of two observed recession limbs showing the approximate values of the two-hourly recession constant for groundwater flow.

rises above the lower limit of the upper permeable layer, interflow occurs. This was simulated in the following way:

If SG(ICOL) (computed by formula(24)) > GMA

then SI(ICOL) = SG(ICOL) - GMA (27)

SG(ICOL) = GMA (28)

in which SI is the actual subsurface storage. All calculations were again performed in mm.

This subsurface storage also has a maximum storage capacity (GMI) when the soil is completely saturated to its surface. To this model parameter a value of 9 mm was assigned. As happened with GMA, this parameter value was achieved by trial and error analysis within a limited range of feasible values. If an average specific yield value of 0.20 is assumed for the upper peat layer (see 3.2.2), 9 mm of water storage variation will correspond to 4.5 cm of water table level fluctuation. This will also mean that the upper peat layer is assumed, in the model, to stop approximately 4.5 cm below the surface. Thus the assumed value for GMI is in reasonable agreement with the conclusions derived from the runoff plots and from the specific yield data (see 3.4.2) according to which the depth of the upper permeable layer is of the order of 5 - 10 cm.

If SI, computed by formula (27) is bigger than GMI then the following calculations are performed:

R1(ICOL) = SI(ICOL) - GMI (29)

SI(ICOL) = GMI (30)

in which R1 is the rainfall excess (mm) which originates surface flow. As was mentioned (see 3.3.2), no significant overland flow was measured from the strips during all the period of records available from the runoff plots. Nevertheless it was assumed, for modelling purposes, that this kind of flow could probably occur during extremely wet conditions.

If the initially computed value of SG is smaller than GMA, none of the computations represented by equations (27), (28), (29) and (30) take place and SI(ICOL) and R1(ICOL) equal zero.

The subsurface storage is also considered as a linear storage and, once the actual value of SI is known, interflow is computed by the formula:

$$QI(ICOL) = SI(ICOL) \times RI \qquad (31)$$

in which RI is the subsurface storage constant. Interflow is computed from the subsurface storage value of the same time-step and thus no lag is considered in the response of the upper peat layer to rainfall. RI is a model parameter and its value can be computed by the formula (Leavesley, 1973):

$$RI = (1 - Kri) \qquad (32)$$

in which Kri is the recession constant of interflow. The two-hourly recession constant of interflow was estimated analysing semilogarithmic graphs of recession limbs of several hydrographs by the method described by Schulz (1973). According to this method the interflow recession limb can be calculated, provided the influence of overland flow is avoided, as the simple difference between the recession limb of the recorded hydrograph and the groundwater recession limb previously separated, in the present case assuming a Kr of 0.98. In the study area overland flow stops quickly after the rain (see 3.3.2) and its possible interference on the calculations was avoided by ignoring the first 6 hours of data after the rain stopped. On the other hand, interflow only occurs when the water table is very high (see 3.3.2) and thus the described method is only applicable during such wet conditions. During the two recession limbs already presented in Figure 33, the water table was very high and thus these events are liable to be analysed in respect to interflow. Figure 34 shows the interflow recession limbs for the two mentioned events together with the approximate values of the two-hourly interflow recession constant (Kri). According to Figure 34, Kri is of the order of 0.75 - 0.76 and thus, according to equation (32), RI has a value of 0.24 - 0.25. However, and contrary to what happened with the groundwater recession constant, the estimated Kri for different analysed events showed some scatter. On account of this, the final value of the model parameter RI was achieved by trial and error within a limited range of feasible values. A final value of 0.20 was assigned to RI.

Once QI is calculated, SI is again updated by the formula:

SI(ICOL) = SI(ICOL) - QI(ICOL). (33)

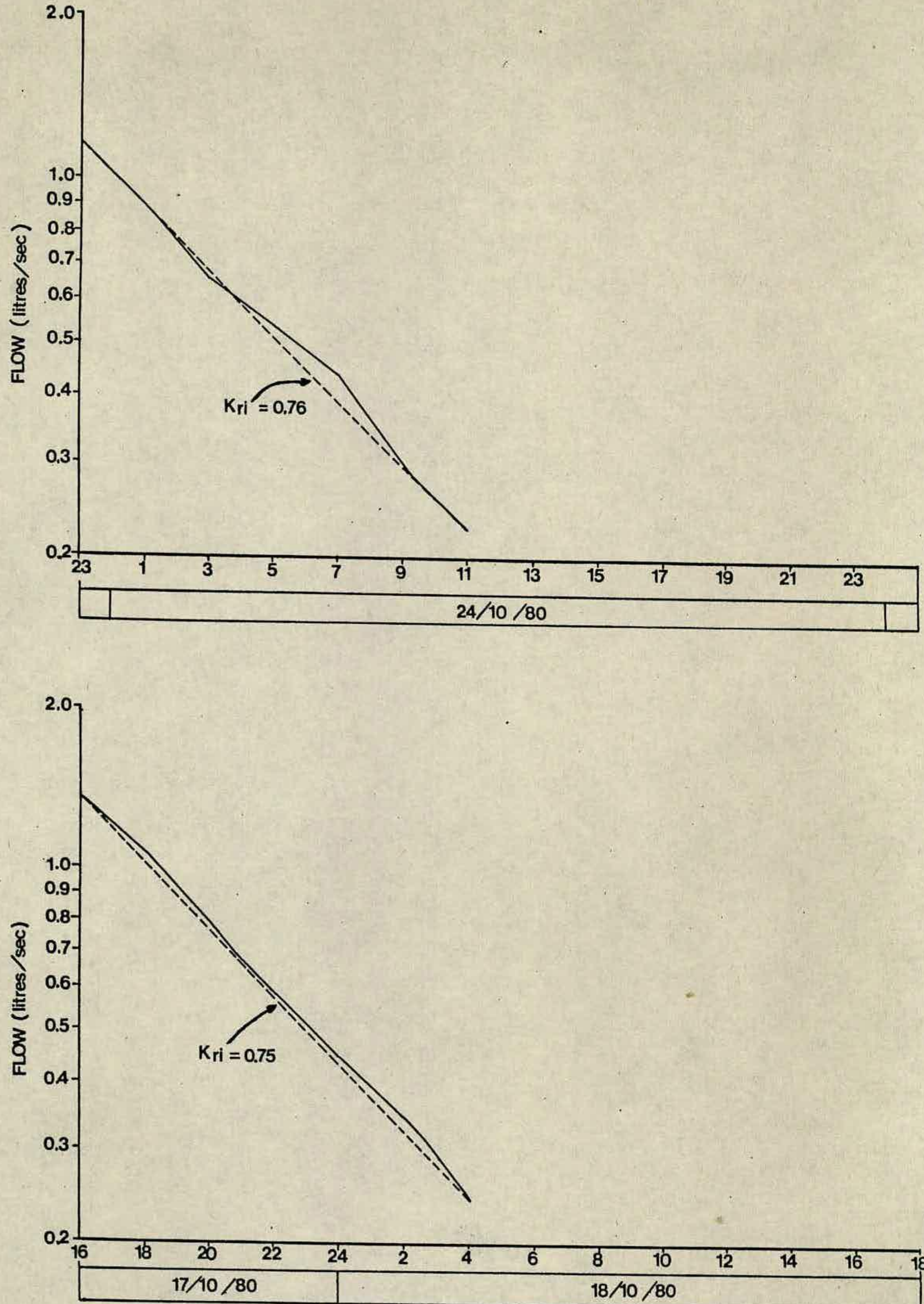


Figure 34 : Analysis of two interflow recession limbs showing the approximate values of the two-hourly recession constant for interflow.

At the beginning of each run of the model initial values must be assigned to SG and SI. These parameter values (SGO, SIO) can be estimated approximately from the observed flows at that time by equations (25) and (31). These initial storage values were however slightly adjusted by trial and error optimization.

For the first two-hourly time-step of each day SG(ICOL - 1) and SI(ICOL - 1) are substituted in equation (24) by SGO and SIO. These two values are updated to allow the initialization of the computations for the following day by making them equal to the last storage values of the current day:

$$SGO = SG(12) \tag{34}$$

$$SIO = SI(12) \; . \tag{35}$$

Figure 35 represents a simplified diagram of the strip component of the model together with some of the main calculations performed within it. It is important to note that in this figure as well as in subsequent figures the variable ICOL, representing the two-hourly time-step number, will be identified simply as I.

3.5.2.2 The Ditch Slope Component

The ditch slope component attempts to simulate the hydrological behaviour of the ditch slopes. The total area occupied by these slopes (ADS) is a model parameter and has a value of 0.591 ha.

It was previously shown that ditch flow was mainly generated by direct rainfall onto saturated ditch areas.

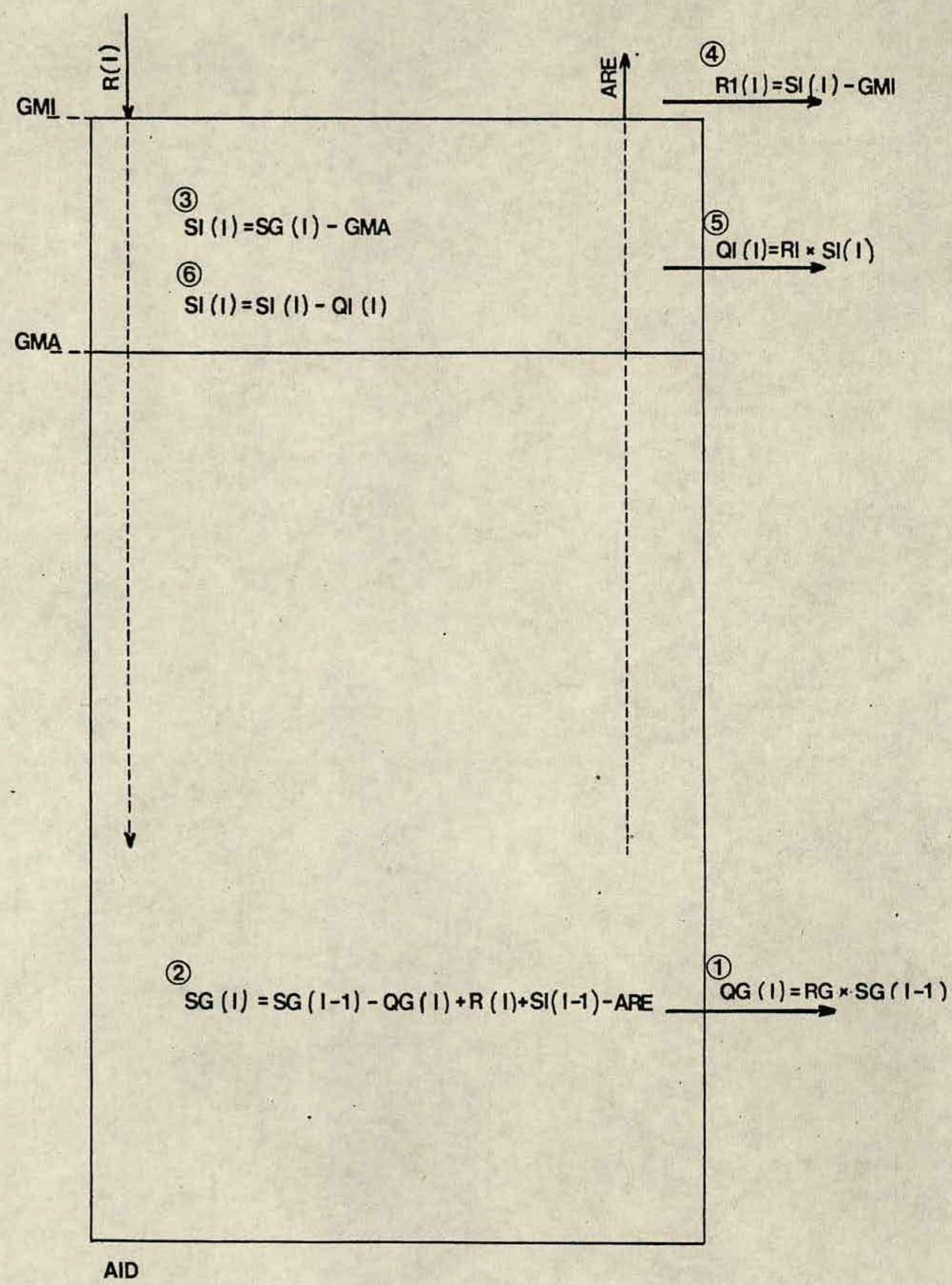


Figure 35: Simplified diagram of the strip component of the model showing the main calculations performed within it. Numbers inside circles indicate the order of the different calculations.

On the other hand it is also known that saturated contributing areas are usually dynamic systems that expand and contract depending on the prevailing moisture conditions (Dunne and Black, 1970b). This concept has been widely applied in conceptual modelling (Huff et al, 1977; Douglas, 1974). It was termed as "variable saturated area" by Douglas (1974) and as "source area runoff" by Huff et al (1977). In the present case, it seemed logical to assume that the saturated ditch slope area was a dynamic system varying in harmony with the water table levels of the neighbouring strips.

To calculate the projected ditch slope area which is working as an impermeable area (PERI) the following assumptions were made:

1. That PERI = 0 when SG is equal or less than zero.
2. That PERI has its maximum value , i.e. the total area of ditch slopes (ADS), when SG is equal to GMA.

Theoretically PERI would only be at its possible maximum when the soil is saturated to its surface, i.e. when SI(ICOL) = GMI. However, as the assumed thickness of the upper peat layer is so small it was found that the subsurface storage of the strip component could be ignored for present purposes.

The ditch slope area can be simulated as a right-angle triangle with the dimensions shown in Figure 36. From the well known geometrical properties of similar triangles (Forder, 1927), it can be easily seen that:

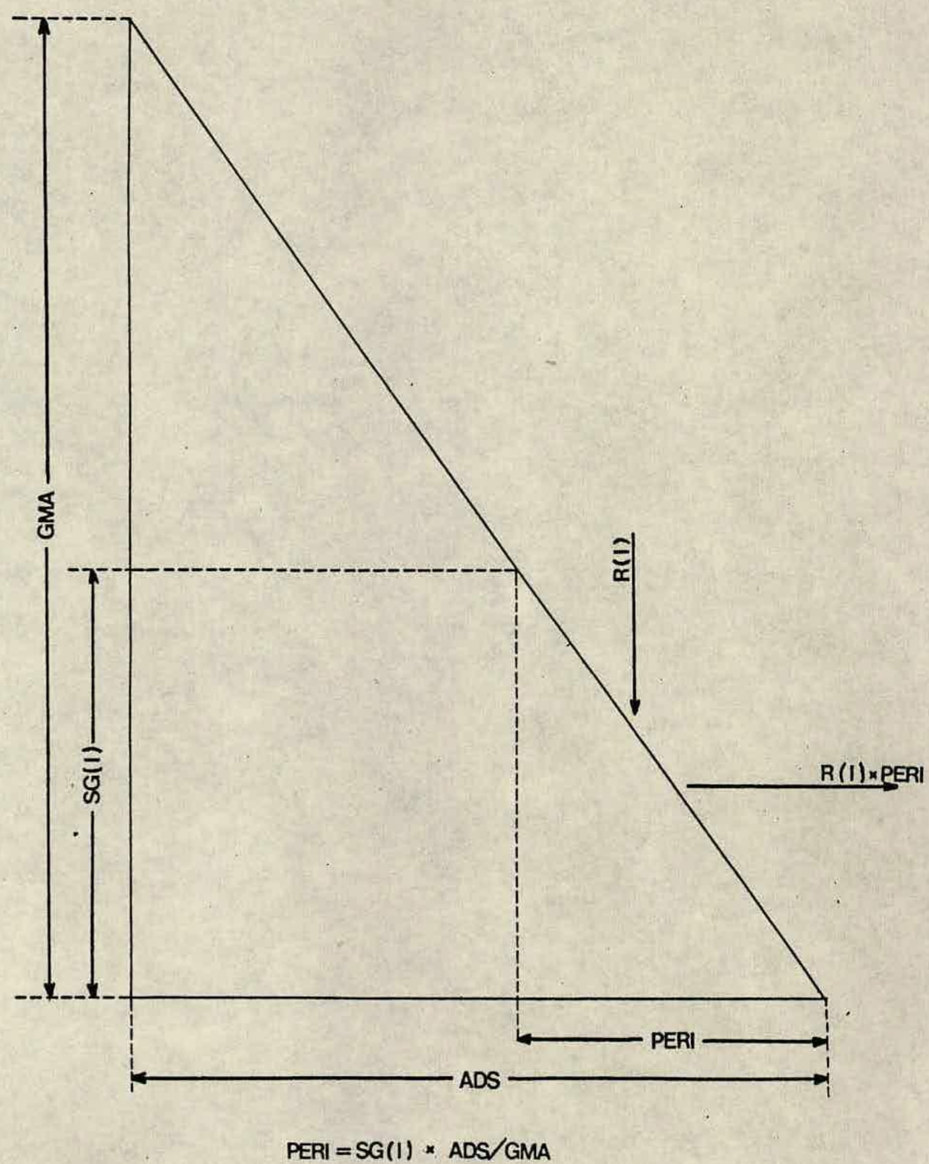


Figure 36 : Diagram representing the ditch slope component of the model.

PERI = SG(ICOL) x ADS/GMA. (36)

The saturated contributing area (PERI) thus expands and contracts according to the actual value of SG. When SG has a negative value, a zero value is assigned to PERI. This procedure is certainly an oversimplification of the hydrologic behaviour of the ditch slopes. Nevertheless it makes them work as a dynamic system and seems to be a reasonable implementation of the "variable saturated area" concept. The volume of saturated overland flow from the ditch slope area can then be easily computed by multiplying the rainfall excess, which equals the total rainfall, and the contributing saturated area (R(ICOL) x PERI). PERI is computed for each two-hourly time-step.

The evaporation from the ditch slopes as well as the rainfall input into the unsaturated part of the ditch slopes do not intervene directly in the hydrological calculations performed on this component of the model. However, the influence of these two hydrological variables is taken into account indirectly when the storage level of the ditch slope component is assumed to be equal to the actual storage value of the groundwater storage of the strips (SG). As was seen in equation (24), SG is a balance of the hydrological inputs and outputs in and out of the strip component. When PERI is computed by formula (36), from the actual value of SG, the model assumes that the rainfall input into the unsaturated area of the slopes together with the evaporation losses induces a variation in the actual storage of the ditch slopes which is equal to the variation of the groundwater storage of the strip component. This simplified procedure is certainly not based on a strong physical knowledge of the hydrological behaviour of the ditch slopes. However, such a simplification could not be avoided because no detailed hydrological studies were carried out on this specific component in the experimental area.

It was shown in section 3.2.2 that the actual evaporation from the ditches was substantially lower than the potential evapotranspiration. This particular finding was not incorporated on the structure of the ditch slope component. However, as the model is particularly intended to simulate the temporal distribution of flow over short periods rather than to perform accurate water balance calculations, this problem is certainly not causing important errors.

3.5.2.3 The Ditch Bottom Component

The ditch bottom component attempts to simulate the hydrological behaviour of the ditch bottoms. The total area occupied by ditch bottoms is a model parameter (AD36), and has a value of 0.162 ha.

The hydrological behaviour of the ditch bottom component is assumed to be controlled by its deficit to saturation (DSB). The inputs into this component comprise groundwater flow and rainfall and the outputs evaporation, groundwater flow and saturated overland flow.

Deficit to saturation is updated during each two-hourly time-step in several stages. Initially, the only considered input into the ditch bottom component is the groundwater flow emerging from the neighbouring strips. As was mentioned earlier (see 3.3.2), at least some groundwater flow enters the ditches through their bottoms. According to the results shown in 3.2.2, evaporation from the ditch bottoms is considered to be a fraction (PEREVA) of the potential evapotranspiration. The first equation used to actualize the deficit to saturation has the following form:

$$DSB(ICOL)=DSB(ICOL-1)+ARE \times PEREVA-QG(ICOL) \times AID/AD36. \quad (37)$$

All terms of equation (37) are expressed in mm. To conserve mass continuity in equation (37), QG, which has previously been computed in mm for the areas of strips, has to be multiplied by its area of origin (AID), then converted into a volume, and then divided by the area of the new ditch bottom component (AD36) to be finally converted into equivalent millimetres for the new reference area. As was mentioned in section 3.2.2, evaporation from the ditches is 48 - 75 % lower than potential evapotranspiration, which is the same as saying that it amounts to 25 - 52 % of the potential evapotranspiration values. A value of 0.35 was assigned to the model parameter PEREVA.

If the calculated value of DSB is negative this means that there is a surplus of water above the saturation level. Under these conditions the following calculations are performed:

$$QG(ICOL) = -DSB(ICOL) \times AD36/AID \tag{38}$$

$$DSB(ICOL) = 0 \ . \tag{39}$$

A new QG value is thus calculated once the deficit to saturation of the ditch bottoms is replenished. QG is again expressed in equivalent millimetres for the initial reference area (AID) by being multiplied by the factor AD36/AID. On the other hand if DSB, calculated by equation (37), is positive it means that groundwater flow input is not enough to completely restore the previously existing deficit to saturation. Under these conditions it is obvious that QG(ICOL) = 0. The rainfall input is then added to restore the remaining deficit to saturation:

$$DSB(ICOL) = DSB(ICOL) - R(ICOL) \ . \tag{40}$$

If the new updated DSB is still positive it means that even with the new rainfall input, the deficit to saturation is not completely restored, thus:

$$R(ICOL) = 0 \tag{41}$$

which means that there is no rainfall excess to generate overland flow. On the other hand, if DSB calculated by equation (40) is negative there will be some rainfall excess and the following calculations are made:

$$R(ICOL) = -DSB(ICOL) \tag{42}$$

$$DSB(ICOL) = 0 \ . \tag{43}$$

If the value of DSB initially computed by equation (37) is negative, equations (40), (41), (42) and (43) are ignored and the rainfall excess is equal to the total rainfall input.

The volume of saturated overland flow from the ditch bottom component can then be calculated as R(ICOL) x AD36.

At the beginning of each run of the program an initial value is assigned for DSB (DSBO). This model parameter is adjusted by trial and error within a range of feasible values. The DSB value of the last two-hourly step of each day is transferred to the next day to allow initialization of calculations for that day.

Figure 37 represents a simplified diagram of the ditch bottom component together with some of the main calculations performed within it.

3.5.2.4 Computation of the Total Output

The previous sections describe how the separate outputs from the different components of the model were computed. These partial outputs are finally integrated to produce a total flow output. The calculation of the total model output follows several steps.

Firstly all rainfall excesses from the different components are integrated to produce a total rainfall excess. To preserve mass continuity, the different rainfall excess components, occurring during each two-hourly time-step, are firstly expressed in volumes and then converted into equivalent millimetres for the final

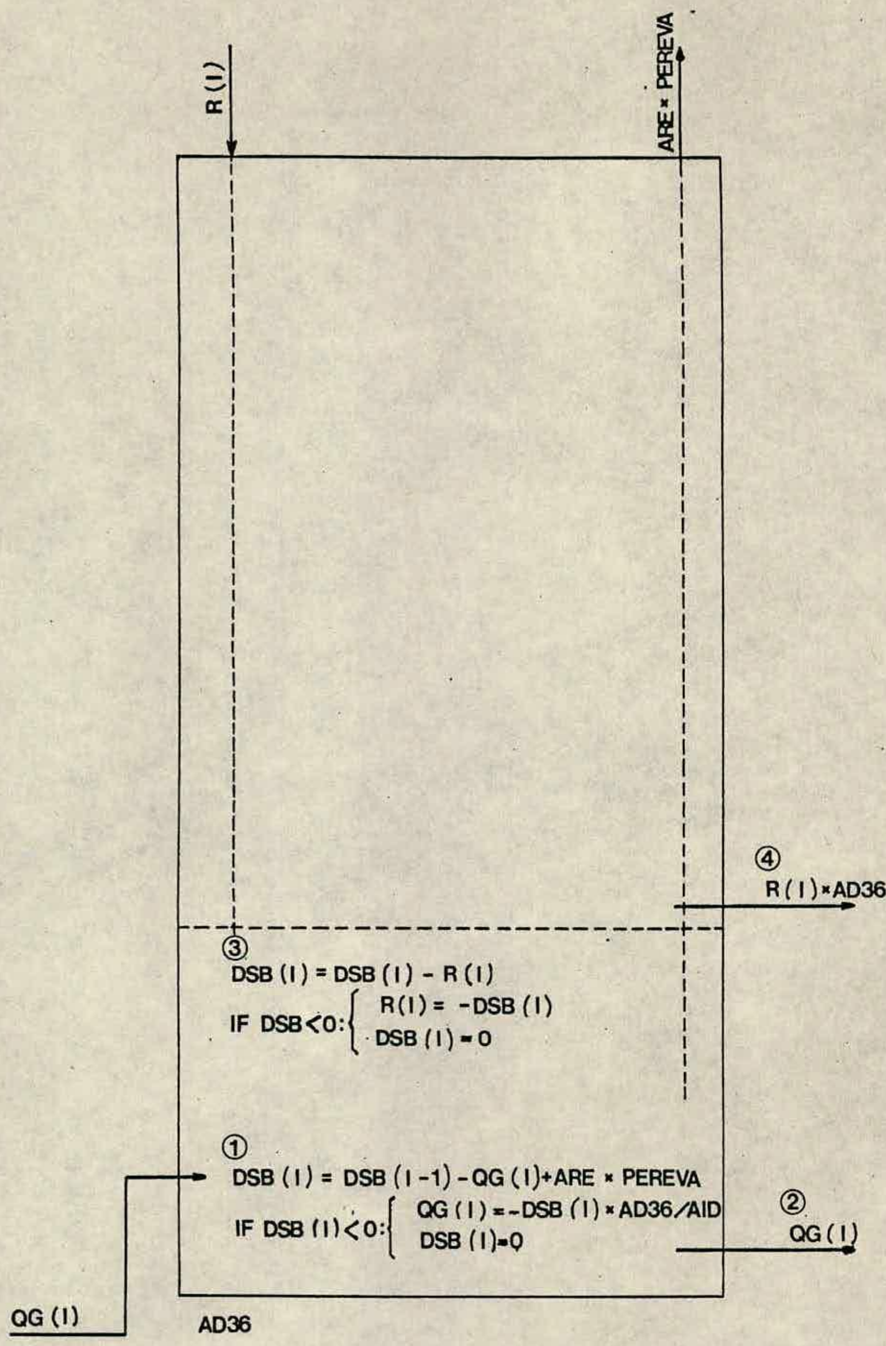


Figure 37 : Simplified diagram of the ditch bottom component of the model showing the main calculations performed within it. Numbers inside circles indicate the order of the different calculations.

reference area which is the total area of the site:

$$AUX=(R(ICOL)\times(AD36+PERI)+R1(ICOL)\times AID)/(AID+AD36+ADS). \quad (44)$$

In equation (44) $R(ICOL)\times(AD36 + PERI)$ is the volume of rainfall excess from the ditch areas, $R1(ICOL)\times AID$ is the volume of rainfall excess from the strip areas and AUX is the total rainfall excess expressed in equivalent mm with the total area as its reference.

The total rainfall excess for each time-step (AUX) is then routed by the unit hydrograph method. A unit hydrograph is defined as the hydrograph of surface run-off which would be generated by a unit depth of rainfall excess occurring within a specific duration of time (Schulz, 1973). Unit hydrographs were computed from several recorded floods by the method described by Schulz (1973). Firstly groundwater flow and interflow components were separated using semilogarithmic graphs of the recession limbs, and then the surface flow hydrograph was computed simply as the difference between the total flow and the sum of the two flow components previously separated. If the rainfall excess is known, the unit hydrograph is easily computed from the surface flow hydrograph employing the principle of proportional ordinates (Schulz, 1973). The rainfall excess, i.e. rainfall that is actually causing the surface flow, could be assumed, for wet periods, as equal to the total rain falling directly into the ditches. It is in fact known that during such periods the ditches work as impermeable areas (see 3.2.2). Surface flow from the strips is usually insignificant (see 3.3.2) and could be ignored for the present purposes. Several flood analyses indicated that a two-hourly unit rainfall excess, occurring during a time-step ICOL, generates a unit hydrograph with, approximately, the following characteristics of temporal distribution:

$$Y1 = 0.582 \tag{45}$$

$$Y2 = 0.347 \tag{46}$$

$$Y3 = 0.071 \tag{47}$$

in which Y1, Y2 and Y3 are the proportions of the total surface flow occurring respectively during the two-hourly time-steps ICOL, ICOL + 1 and ICOL + 2. Y1, Y2 and Y3 are model parameters.

The total rainfall excess (AUX) is then routed by the unit hydrograph method using the following procedure:

$$QS(ICOL) = QS(ICOL) + AUX \times Y1 \tag{48}$$

$$QS(ICOL + 1) = QS(ICOL + 1) + AUX \times Y2 \tag{49}$$

$$QS(ICOL + 2) = QS(ICOL + 2) + AUX \times Y3 \tag{50}$$

in which QS is the surface flow output in mm/2h. From the previous calculations it can be seen that up to three different two-hourly rainfall inputs can contribute to the surface flow of the same time-step.

The final total flow output is calculated by adding the surface flow output, the groundwater flow output and the interflow output:

$$QT(ICOL) = QS(ICOL)+(QG(ICOL)+QI(ICOL)) \times AID/(AID+AD36+ADS) \tag{51}$$

in which QT is the total output, in mm/2h. QG and QI, originally expressed in equivalent millimetres for the strip area have to be converted into a volume basis by being multiplied by their area of origin (AID), and then divided by the total area of the site to be expressed finally in equivalent millimetres with the total area as reference.

Total flow output was calculated on a two-hourly basis. The output of the computer program provides two-hourly as well as daily flow estimates. Daily flows (QT2) were computed by simply adding the 12 two-hourly flow estimates of each day. QT is expressed in mm/2h and QT2 in mm/day.

3.5.2.5 The Error Function

The accuracy of a model is fixed by establishing a criterion of goodness of fit for its simulated response to that of the recorded catchment response (Fleming, 1975). This criterion is usually established by selecting an error function which compares computed and observed flows. The error function used in the present model is that described by Douglas (1974), Fleming (1975) and Nash and Sutcliffe (1970) and is calculated by the computer program in several steps. Firstly the sum of the squares of the differences between observed and computed outputs is calculated:

$$F = \sum_{ICOL = 1}^{600} (QT(ICOL) - QOB(ICOL))^2 \qquad (52)$$

in which QT are the computed flows and QOB are the observed flows. The F value is calculated for the 600 two-hourly time-steps of each model run.

The sums of the observed and computed flows are also calculated:

$$SUMO = \sum_{ICOL=1}^{600} QOB(ICOL) \tag{53}$$

$$SUM = \sum_{ICOL=1}^{600} QT(ICOL)\ . \tag{54}$$

The magnitude of the F value is dependent both on the goodness of fit of the model and on the magnitude and variation of the observed output data (Douglas, 1974). This variation in the observed flows can be expressed by the sum of the squares of the deviations of the observed flows from their mean:

$$FO = \sum_{ICOL=1}^{600} (QOB(ICOL) - SUMO/600)^2. \tag{55}$$

The error function (R2) is finally calculated by the formula:

$$R2 = 100 \times (FO - F)/FO\ \%\ . \tag{56}$$

This error function calculates the percentage of the sum of the squares FO, of the observed flows, which is explained by the model (Douglas, 1974). This also means that R2 calculates the percentage of the variance of the observed output which is explained by the model. R2 is usually termed "efficiency". The value of this function can vary from $-\infty$ to + 100 %. A negative value indicates that the model produces a worse estimate than the simple mean of the observed flows, and a value of 100 % indicates that F equals zero and thus all computed values are exactly equal to the corresponding observed flows (Douglas, 1974).

A similar error function (R22) was also used to compare daily computed flows (QT2) with daily observed flows (QOB2).

As was mentioned earlier the values of some model parameters were adjusted slightly by trial and error. The very simple procedure used, consisted of changing each parameter by small increments, and seeing the influence of these changes on the values of the error functions R2 and R22. In some published models, parameter values were found by automatic parameter optimization. According to Fleming (1975), this is an attempt to introduce into the program the ability to assign final parameter values that best satisfy the selected accuracy criterion. Automatic parameter optimization does not involve the manual parameter adjustments which are used in the trial and error method. Automatic parameter optimization was not used in the present model because it was thought that the parameters values should be based as much as possible on the experimental results and only slight adjustments were found necessary within very limited ranges of feasible values. In fact even the use of a trial and error method for parameter optimization does to some extent weaken the use of the model as a validation of the main experimental findings. However, slight adjustments of some parameter values could not be avoided as the experimental results were not quantitatively very precise in some cases.

3.5.2.6 Concluding Comments on the Model Structure

The separate structures of the different parts of the computer program have been described in the previous sections. The equations shown represent the main calculations performed by the computer program. However, further details concerning these calculations are available and are given in Appendix 7 in which the whole computer program, written in a local version of Fortran, is presented. Table 12 shows a simplified flowchart of the computer program, constructed according to the conventions described by Chapin (1974). Figure 38 presents a simplified diagram of the general structure of the model. Figure 38 shows the different inputs and outputs of the different components of the model as well as the way in which the total output is calculated.

3.5.3 Results

As was said earlier the model was tested for three Autumn periods of fifty days. These periods were: 28 August - 16 October, 1977, 4 October - 22 November, 1978, and 17 September - 5 November, 1979. All these

- Initialize arrays and variables.
- Read model parameters.
- Loop over 50 days.
  - Read: two-hourly rainfall, two-hourly observed flows and daily evapotranspiration.
  - Loop over 12 two-hourly time-steps of each day.
    - STRIP COMPONENT

      Compute groundwater flow, interflow and rainfall excess.
    - DITCH SLOPE COMPONENT

      Compute area of ditch slopes working as impermeable.
    - DITCH BOTTOM COMPONENT

      - Update groundwater flow after routing through deficit to saturation.
      - Compute rainfall excess.
    - Compute two-hourly surface flow.
    - Compute two-hourly total flow.
    - Update:- sum of square of deviations between two-hourly observed and computed flows.
      - sum of observed two-hourly flows.
      - sum of computed two-hourly flows.
    - Compute daily flows
    - End of loop looking at each two-hourly time-step.
  - Transfer final two-hourly storages of groundwater, subsurface storage and deficit to saturation to start of next day.
  - Transfer two time-steps of surface flow to start of next day.
  - Update:- sum of observed daily flows.
    - sum of computed daily flows.
    - sum of square of deviations between daily observed and computed flows.
  - End of loop looking at each day.
- Compute error function for two-hourly and daily flows.
- Write model output: two-hourly and daily computed and observed flows together with their sums and error function values.

TABLE 12: Simplified flowchart of the computer program.

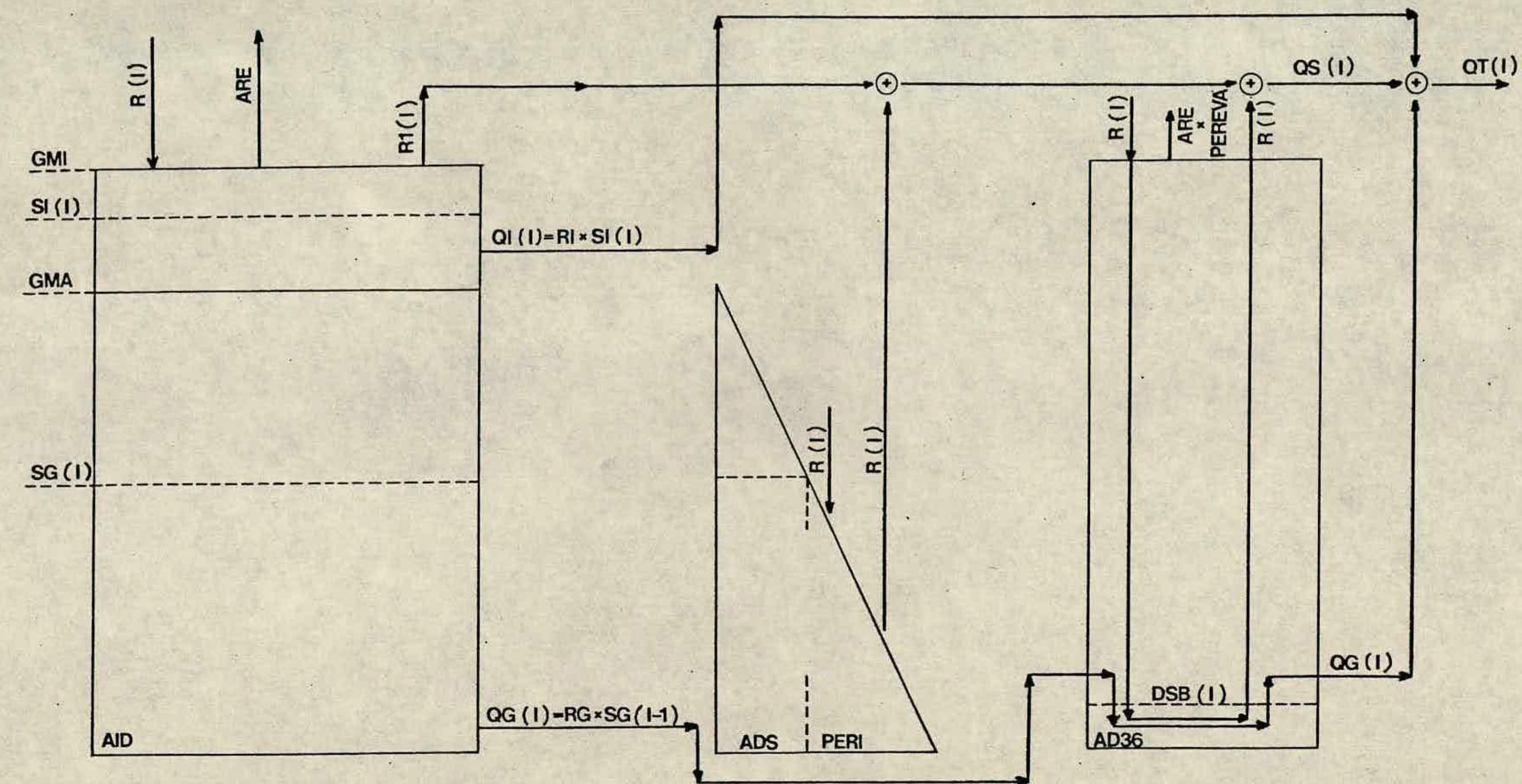


Figure 38 : Simplified diagram of the general structure of the model.

periods were free of ice and snow effects and thus the measured flows at the V-notch weir can be regarded as reliable (see 2.1.4). Figures 39 and 40 show respectively the two-hourly and daily computed flows compared with the corresponding observed flows for the 1977 period, Figures 41 and 42 show similar graphs for the 1978 period and Figures 43 and 44 are identical graphs for the 1979 period. Appendix 8 shows detailed information on the values of the model parameters, on the input data files and on the output of the model for the 1978 run. The graphs presented in Figures 39, 40, 41, 42, 43 and 44, were drawn from the numerical outputs of the model using an available computer package programmed by Dr. R. Mutzelfeldt. From the graphs presented it can be seen that the error function for the two-hourly flow estimates varies for the different periods from 87.6 % to 95.3 %. For daily flow estimates it varies from 91.9 % to 97.6 %. If it is remembered that the value of this error function represents the percentage of the variance of the observed flows explained by the model, the results indicate that the model yields flow rate estimates which are in good agreement with the corresponding observed values. It is important to note that the same parameter values were used for all the three periods of calculations. The only values that were adjusted for each specific period were the initial values of groundwater storage (SGO), subsurface storage (SIO) and deficit to saturation of ditch bottoms (DSBO). It is also interesting to note the reasonable agreement between the totals of computed and observed flows for each of

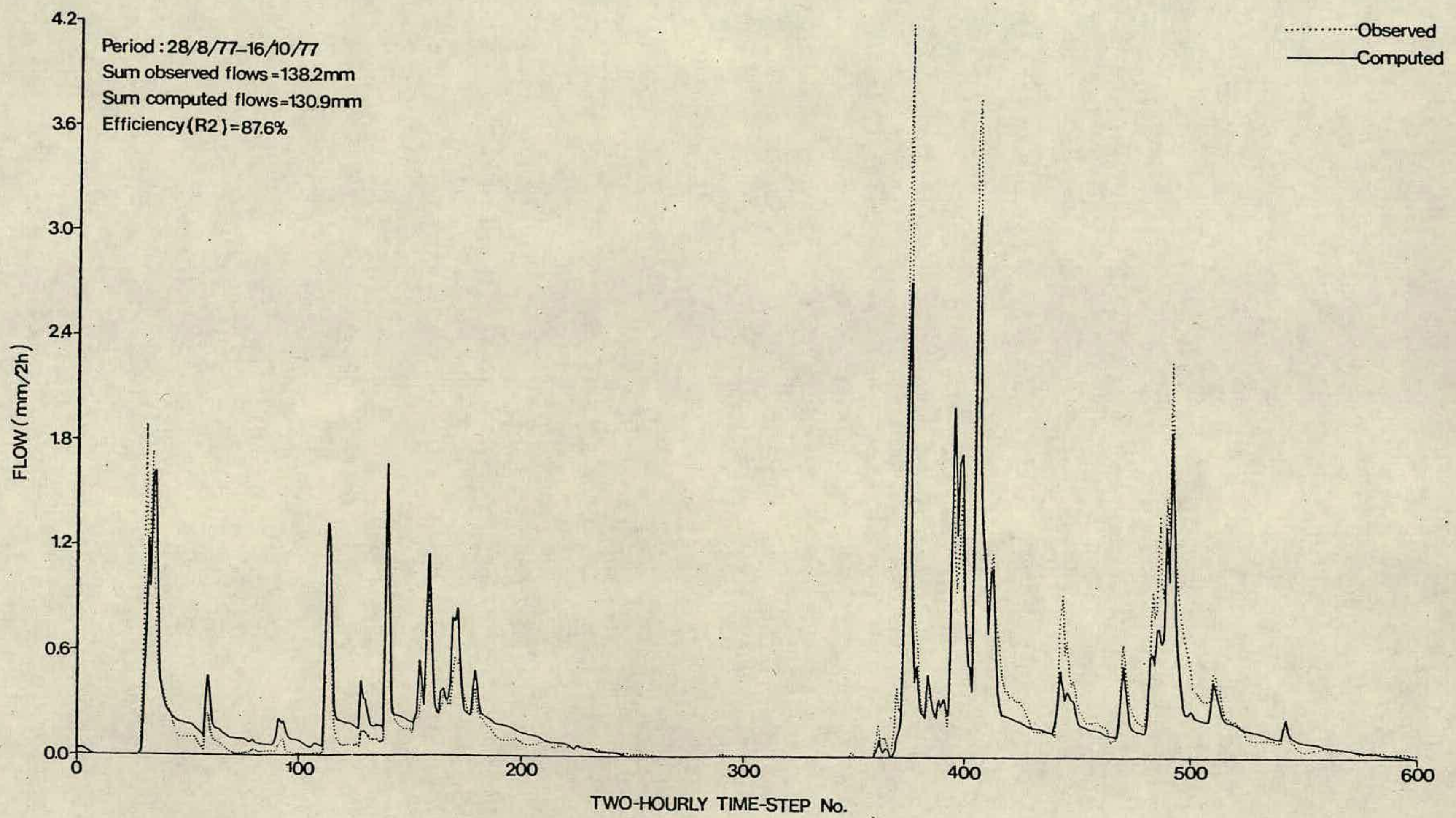


Figure 39 : Two-hourly computed and observed flows for the model run for 1977.

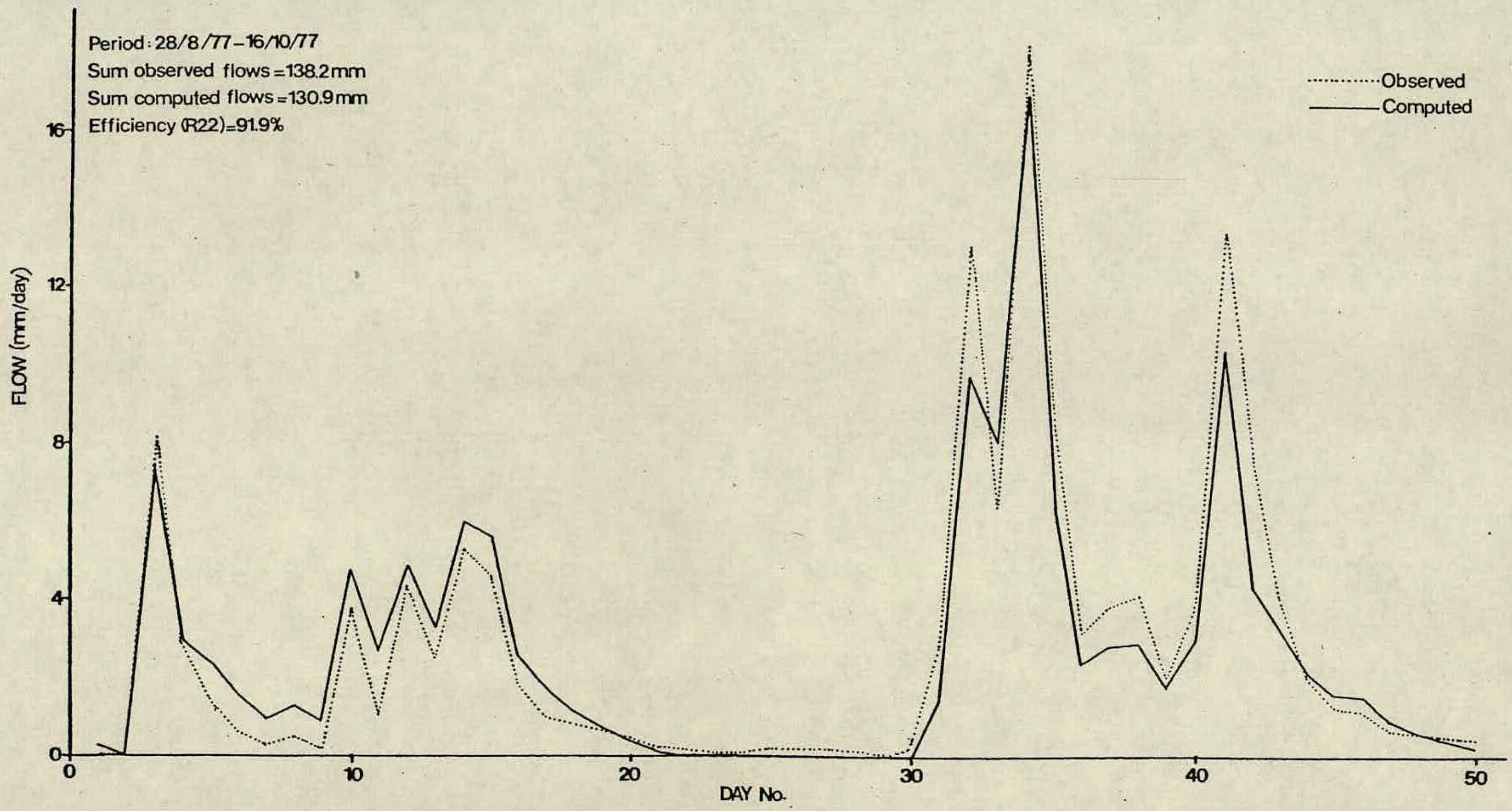


Figure 40 : Daily computed and observed flows for the model run for 1977.

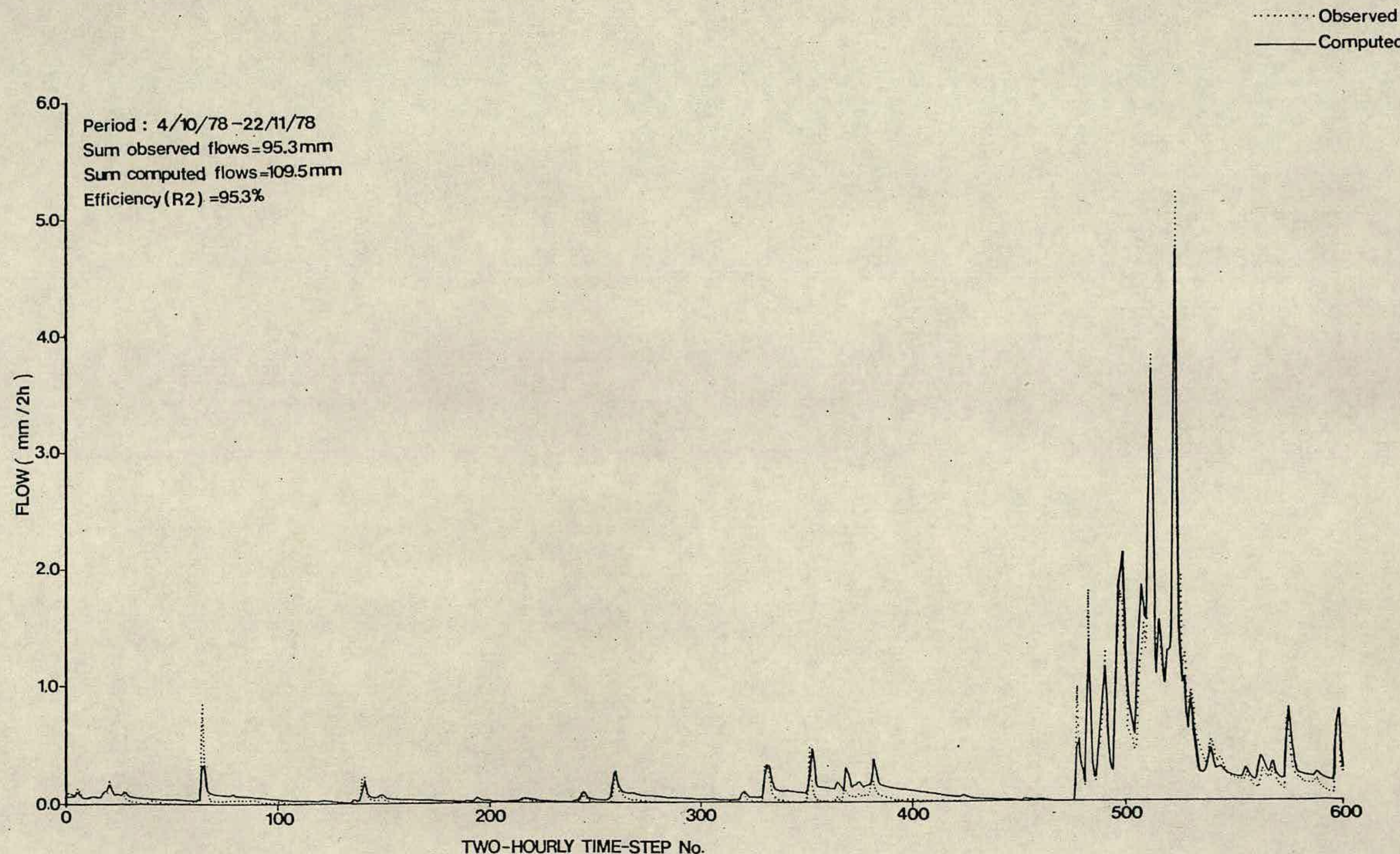


Figure 41 : Two-hourly computed and observed flows for the model run for 1978.

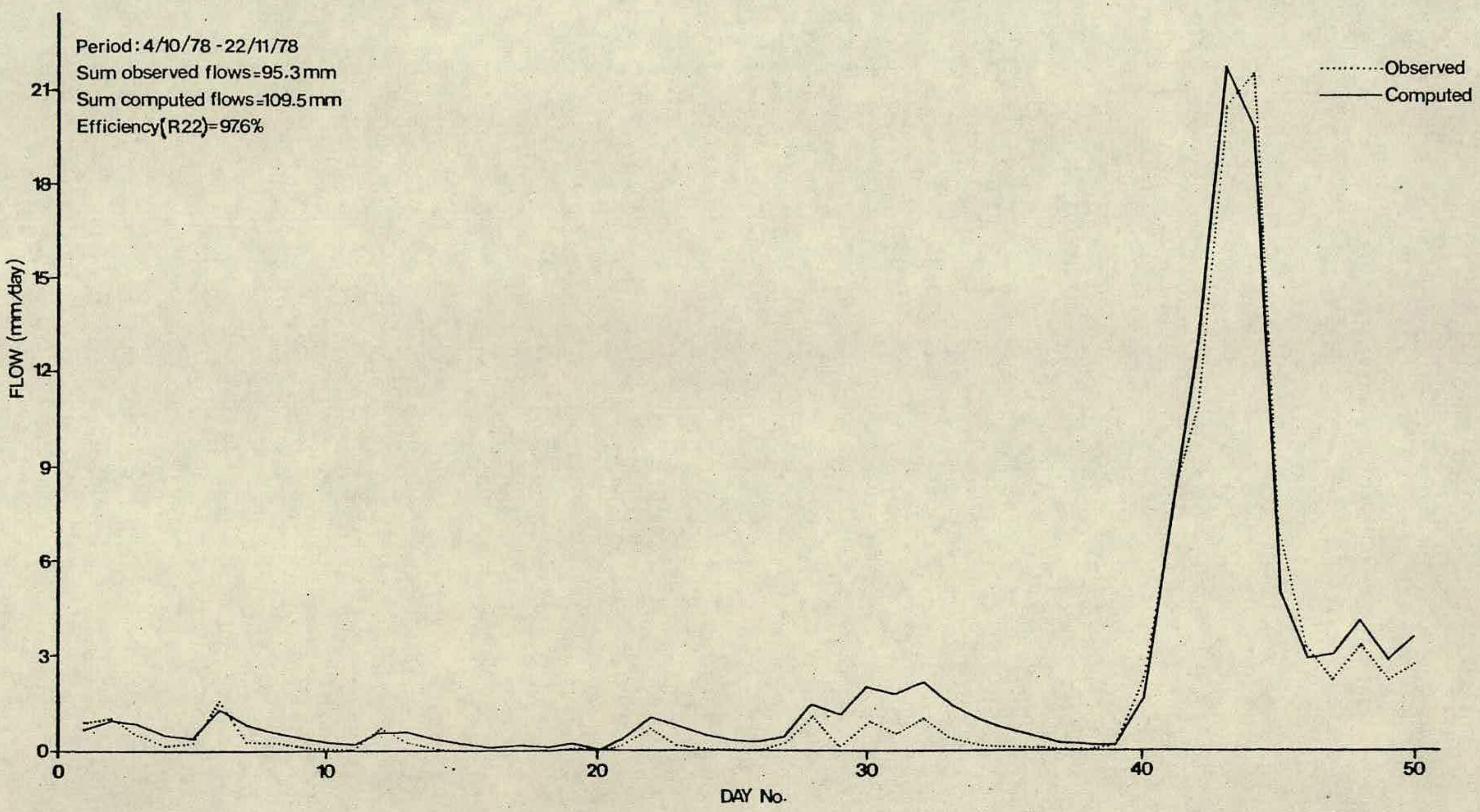


Figure 42 : Daily computed and observed flows for the model run for 1978.

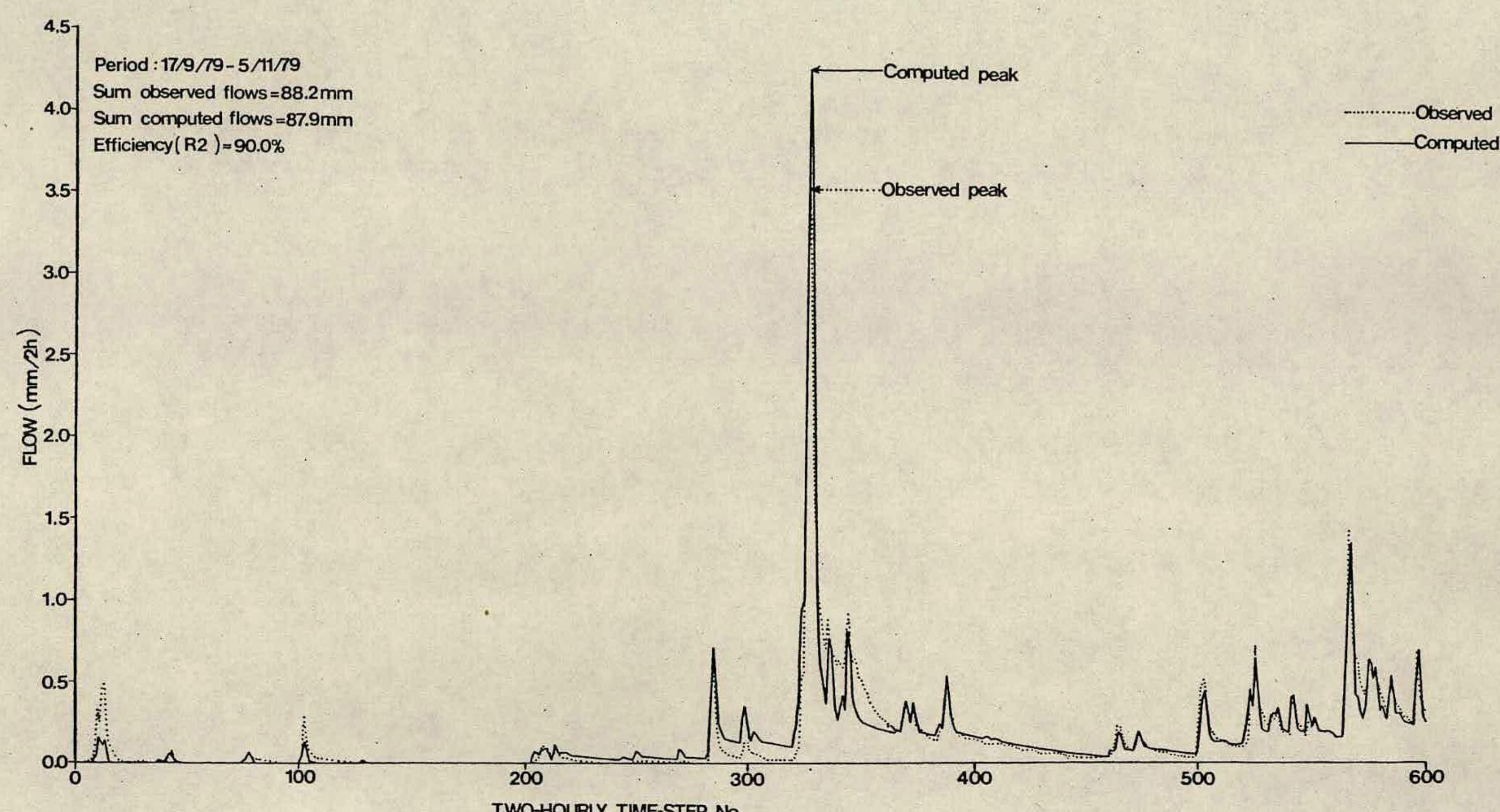


Figure 43 : Two-hourly computed and observed flows for the model run for 1979.

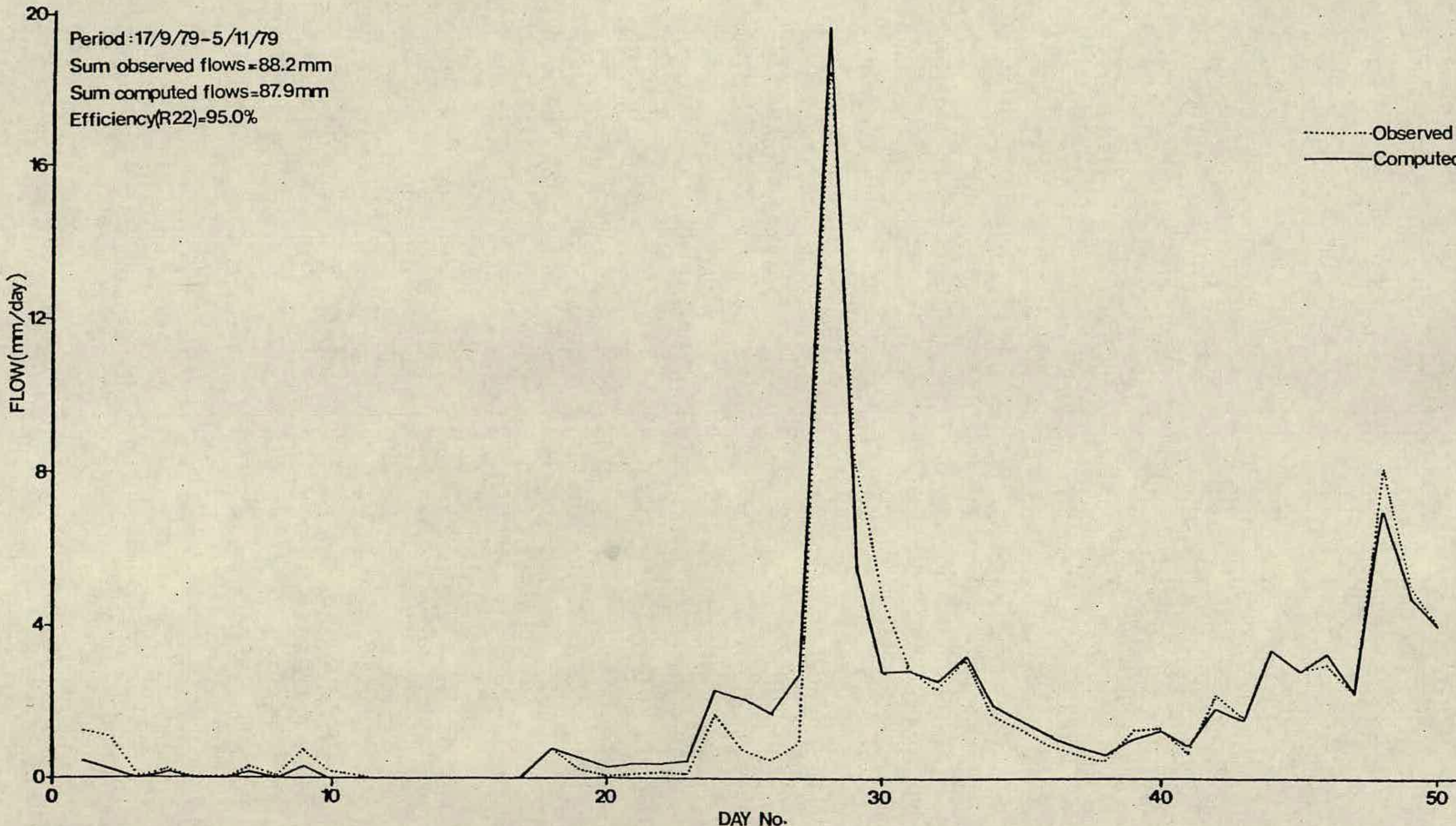


Figure 44 : Daily computed and observed flows for the model run for 1979.

the three periods. The maximum percentage deviation between total computed flow and total observed flow amounted to 15 %, during the 1978 period.

As should be expected the fitting between computed and observed flows is better for daily, than for two-hourly, flows. As was already described, rainfall rates measured at the tilting-siphon raingauge recorder could only be read with some accuracy for a minimum time-step of two hours. For such small time-steps it was difficult to be sure that the timing between these rainfall readings and the flow readings from the V-notch weir was correct. As a consequence, some timing errors were certainly introduced into the two-hourly flow predictions. These timing errors are certainly attenuated when the two-hourly flow estimates are integrated into daily flow estimates. The two-hourly flow estimates were initially conceived only as a mean to achieve good estimates for daily flows. However, the two-hourly flow estimates proved in the end to be themselves a good estimate of the observed temporal flow distribution.

3.5.4 Discussion

The efficiency of flow prediction by a model is obviously affected by possible errors in the basic data of the input files. Possible errors on rainfall and runoff measurements have been previously described on sections 2.1.2 and 2.1.4. Probably the biggest input errors are incorporated in the potential evapotranspiration estimates. Evapotranspiration input into the program consists simply of average daily values obtained from weekly records. As a consequence no precise information is available either on the two-hourly distribution of daily evapotranspiration or on the daily distribution of weekly evapotranspiration. From Figures 39, 41 and 43 it can be seen that the recession limbs of computed hydrographs sometimes drop quicker and other times drop slower than the corresponding recession limbs of observed hydrographs. This may be caused by possible overestimation or underestimation of the true evapotranspiration during such periods of calculations.

The efficiency of prediction of a model can also be affected by possible oversimplifications, in the model structure, of the real behaviour of the physical system. As was mentioned earlier, it is never possible to take into account the complexity of all the physical processes occurring in any specific area (Fleming, 1975; Douglas, 1974).

The present model was intended to be based, as much as possible, on the results of the experimental work. However, some of the experimental findings on which it is based have the disadvantage of not being supported by very precise quantitative conclusions. For instance, it was mentioned in section 3.2.2 that evaporation from the ditches was significantly lower than the evapotranspiration from the strips. From the available data it seems however rather speculative to put a precise figure on the ratio between the evapotranspiration from these two areas. Also, the most intensive experimental work was localized on very specific areas of the site and some caution is needed when the quantitative results of such localized experiments are extrapolated to the whole area. For the reasons outlined some model parameters were adjusted, by trial and error, within a limited range of feasible values. Nevertheless, all parameter values were essentially based on the experimental results.

It was indicated in section 3.3.4 that the experimental conclusion that infiltration is not restricted along the vertical profile of the strips is difficult to explain on a soil physics basis. To test the validity of this conclusion a simple modification was made to the structure of the computer program. Huff et al (1977), in their model, assumed that vertical percolation was numerically equal to the hydraulic conductivity of the soil which is a nonlinear function of water content. Childs (1972) and Rose (1966) showed that, when the soil is near saturation, infiltration capacity equals the saturated hydraulic conductivity. As the autumn periods used to test the model were wet periods, with relatively high water table levels, the lower peat layer certainly remained close to saturation during them. It seemed reasonable then to assume, in this modified version of the model, that the percolation capacity across the boundary between the two peat layers had a constant value equal to the saturated hydraulic conductivity of the lower peat layer, which according to Cuttle (pers. comm.) is 1 cm/day. If the rainfall input exceeds the percolation capacity, a perched saturated storage is created in the upper peat layer and this water is quickly released as interflow. This new version of the model drastically overestimated flood peaks as well as significantly underestimated groundwater flow rates. The efficiency of the model for two-hourly flows, dropped from 87 % - 95 % to values of the order of 50 % - 60 %. This very simple modification of the model indicates that drastic percolation restrictions are certainly not occurring at the boundary of the two peat layers. On the other hand, this small simulation test confirms that the original version of the model is probably close to the truth, which also implies that the experimental conclusion according to which water infiltrates freely to the main water table is also correct. However, this conclusion still remains unexplained from what is known about the soil physics of the peat.

The saturated ditch areas, from which overland flow occurs, work in the model as a dynamic system. During wet periods, when the groundwater storage (SG) equals its maximum capacity (GMA), the entire ditch area works as an impermeable area. The influence of overland ditch flow is so dominant on flood generation that any simple model that takes this type of flow into account will probably predict peak flows with reasonable accuracy. The assumption according to which the two layers of the strips work as linear storages is certainly an over-simplification of their real hydrological behaviour. However, on account of the dominance of ditch flow during storms, possible small errors in the simulation of the response of the strips certainly do not have much effect on the accuracy of peak predictions.

According to the study reported in this section, it seems that the hydrological response of the experimental area can be simulated reasonably if the main experimental conclusions are taken into account. This also means that the results on which the model is based are essentially correct. In the end the hydrological behaviour of the site seems to be simple enough to be simulated reasonably by a model as simple as the one presented in this work. According to Pitman (1978), the most complex model is not necessarily the best for all hydrological problems.

The model was tested only during autumn periods because these were the more critical for the occurrence of floods. The model was not applied to winter or early spring periods because snow and ice significantly affect the hydrological behaviour of the area during such periods and no specific studies were carried out either on the storage of snow or on its melting. Furthermore, data on observed flows are not reliable during such periods (see 2.1.4). The periods of late spring and early summer are of no interest for flow simulation as long dry spells with no flow usually occur at these times.

The eventual merits of the modelling exercise presented in this section must be looked at within its limited intentions of being an additional and integrated way of checking the validity of the main experimental conclusions. Restrictions of time did not allow a more complete simulation study that would include automatic parameter optimization and model sensitivity analysis. However, and taking into consideration the very specific objectives of the present study, the above mentioned aspects were not thought to be particularly important.

The model structure could certainly be improved if more was known about the physics of the water movement through the peat. Furthermore, the model cannot be considered fully tested as it was only applied for the particular conditions of autumn periods. On account of the outlined limitations, the model presented in this work cannot be considered as a final product of a complete simulation exercise liable to be generally used to predict outflows from peatlands recently drained for forestry purposes. Nevertheless, the good results yielded by its application indicate that the present work can be regarded as a possible basis for future and more detailed studies on this subject.

PART 4

CONCLUSIONS

As was indicated in the Introduction (see 1.1), the aim of the work reported in this thesis was to quantify, and seek an understanding of, the hydrological components and processes operating in a peat area newly drained for forestry purposes. The preceding Parts of the thesis have outlined the various experiments carried out in an attempt to achieve these objectives and have shown that the results obtained from this work allow conclusions to be drawn about the water balance, runoff processes and the relationship between water table levels and flow rates. Further conclusions can also be made concerning the applicability of computer simulation models to this kind of study.

As far as water balance studies are concerned, the results show that, over the 3-year study period, actual evapotranspiration from the experimental area as a whole was significantly lower than the estimated potential evapotranspiration. In this respect, the results agree with those published by other workers (Mustonen and Seuna, 1975; Seuna, 1974). At Leadburn, however, this difference was not found to be due to the effects of drainage on the water table and on the natural vegetation of the area. Rather, it was found to be due to greatly reduced evaporation rates from that part of the area consisting of newly ploughed, bare open ditches. The results show that these ditches, which occupy c.30 % of the total area, had water losses to the atmosphere amounting to only c. 40 % of the estimated Penman potential evapotranspiration rate over the 3-year study period. The vegetated strips, on the other hand, where hydrological conditions are specifically intended to be changed by drainage, were rather unexpectedly found to have actual evapotranspiration rates very close to estimated Penman potential evapotranspiration rates.

The fact that the evaporation from the ditches is significantly lower than potential evapotranspiration can be explained by three main reasons: firstly the ditches have almost no vegetation cover, secondly their surfaces dry out during some summer periods and thirdly moisture transfer to the atmosphere is certainly restricted inside the sheltered ditch areas (Verma and Cermak, 1974). It should be borne in mind, however, that Oke (1978) has suggested that ditches can work as radiative traps and that this could increase the evaporation from such areas. Detailed studies on the physics of the evaporation from the ditches were not done in the present work. However, this would certainly be an interesting and important problem worth looking at in more detail in future work.

The unexpectedly high evapotranspiration losses from the vegetated strips can also be explained quite satisfactorily. Evapotranspiration from such areas is influenced both by their vegetation cover and by the moisture content of the upper peat layers. The natural peat vegetation of the site had the particular feature of including the species <u>Calluna vulgaris</u> which grows better in drained than in waterlogged peat soils (Gimingham, 1972; Department of Agriculture and Fisheries for Scotland, 1965, 1964). Thus it seems reasonable to expect that, in the present case, evapotranspiration from the strips would not be as much reduced after drainage as has been found in other drained peatlands where the whole natural vegetation was adversely affected by drainage. Furthermore, data from the lysimeters indicate that the uniformly wet regime of the local climate together with the high water holding capacity of the peat greatly restrict the occurrence of major soil moisture deficit events which could restrict actual evapotranspiration from the strips. The fact that actual evapotranspiration from the strips has values close to the Penman potential evapotranspiration is thus in general agreement with what might be expected under such conditions. However, the fact that strip evapotranspiration equals the potential evapotranspiration does not necessarily mean that it also equals the pre-drainage evapotranspiration of the bog, for it has been shown that actual evapotranspiration from undrained bogs can be significantly higher than evaporation from open water (Nichols and Brown, 1980; Sturges, 1968a).

As with the water balance studies so the work on runoff processes also showed the importance of distinguishing between the respective hydrological behaviours of the strips and of the ditches. Several conclusions can be drawn from the experiments carried out on runoff processes.

The first is that the ditches do, to all intents and purposes, behave as impermeable areas during wet periods. Many authors have previously suggested that a network of open ditches speeds up the hydrological response of recently drained peatlands (Ahti, 1980; Binns, 1979; Mustonen and Seuna, 1975; Seuna, 1974; Howe et al, 1966). However, in these works very few data were presented to prove or explain this fact. The present work clearly demonstrates that rain falling directly onto the ditches originates an immediate response of saturation overland flow which explains the very sharp and well defined peaks of storm hydrographs.

The second conclusion from the runoff processes work, is that rain falling onto the strips between ditches can take different paths through the soil, depending on the prevailing moisture conditions. The most common type of flow from the strips is groundwater flow slowly released by the deeper and more decomposed peat layers. Some of this water enters the ditch bottoms by vertical upward movement from below. This type of groundwater flow sustains the long hydrograph recession limbs. When the water table is high and located within the upper permeable peat layer, a quick interflow response emerges from the strips. Overland flow was never recorded from the strips. Flow from the strips stops completely when the water table depth is 40 - 45 cm below the centre of strips between 60 cm ditches and 45 - 50 cm below the centre of strips between 90 cm ditches. Further lowering of the water table below the above levels is accomplished only by evapotranspiration.

Some difficulties were experienced in explaining some of the above conclusions on runoff processes on a soil physics basis. According to the data available infiltration does not seem to be restricted along the vertical profile of the strips in spite of the very different permeabilities of different peat layers. Theoretically, percolation restrictions should be expected to occur at the boundary between the upper and lower peat layers, particularly during storms of high rainfall intensity. Under these conditions a perched saturation zone should occur above the boundary of the two layers and so-called "throughflow" (Weyman, 1973) should then occur. However, this situation never seemed to happen and the existence, or non-existence, of interflow seems only to be related to the preceding water table level, and not at all with rainfall intensity. A sound and physically based explanation for this fact was not completely achieved and further work on this subject should be done in future studies.

Another area of investigation about which conclusions can be drawn from this thesis concerns the relationship between water table levels and flow from the strips. This relationship was studied during rainless periods when ditch flow does not exist and the total flow from the entire area consists solely of flow from the strips. An attempt was made to study this relationship by the method derived by Romanov (1968b) for undrained areas. It was hoped that the method together with the knowledge that during wet periods the ditches work as impermeable areas would eventually allow runoff from the area to be predicted solely from water table and rainfall data. However, the data available were not sufficient to define the relationship between flow from strips and water table depth with real confidence. Furthermore, for high water table levels, the flow rates from the strips seemed to be almost independent of the water table levels. For these reasons the relationship between water table depth and flow from strips was not used for runoff prediction in the present study.

The modelling work reported in this thesis also produced some interesting results. This work was undertaken specifically to provide an additional and integrated way of checking the validity of the main experimental findings. The model was constructed taking into account the main conclusions drawn about the runoff processes operating in the area. According to Douglas (1974), if a model is a good representation of the physical system its output will approximate closely to the real output from the physical system. The model was applied to three autumn periods, each of fifty days duration, to estimate two-hourly and daily flows solely from rainfall and evapotranspiration data. The efficiency of the model ranged from 87 - 95 % for two-hourly flow predictions and from 91 - 97 % for daily flow predictions. The efficiency values represent the percentage of the variance of the observed output explained by the model. The good flow estimates yielded by the model certainly mean that the experimental conclusions on which its structure was based are essentially correct. The encouraging results from the modelling exercise reinforce the views of Dooge (1975) and Zubets and Murashko (1975) that an increase in the use of mathematical models in peat hydrology can contribute significantly to improving knowledge about the hydrological behaviour of such areas.

All the above conclusions have emphasized the dominant importance of the open ditches on the different aspects of the hydrology of the site. The results of this research indicate that recognition of this fact is of great importance when the hydrological behaviour of recently drained peatlands for forestry purposes is compared with the hydrological behaviour of either undrained peatlands or peatlands drained for agricultural purposes. It is unfortunate that this fact has not been more widely recognised in the literature, as failure to appreciate it has undoubtedly contributed towards the controversy that exists about the hydrological effects of peat drainage. It must also be recognised, however, that short-term and long-term influences of forest drainage are quite different (Heikurainen _et al_, 1978;

Kuntze, 1974). The present study was carried out on a recently drained area and thus is only relevant to the short-term aspects of forest drainage influences.

Several other aspects related to the type of vegetation and type of peat must also be taken into consideration when comparisons are made between the results of the present study with the ones reported for other areas. As was mentioned earlier, different original vegetation covers may react to the water table drop caused by drainage in completely different ways. Different peat types may also have quite different hydrological features. According to Dooge (1975), peat formations may be divided basically into two main subdivisions: bogs and fens. The term bog is usually applied to peat formations where the only inflow is direct rainfall and the term fen is used for areas where, together with rainfall, groundwater inflow from the surroundings is also appreciable. The present study was carried out on a recently drained raised bog and thus is only relevant for aspects related to forest drainage influences on the hydrology of bogs. It is also important to bear in mind that, because of experimental difficulties, the study reported in this thesis does not take into account aspects of the hydrology of winter periods affected by frost and snow. The lack of winter period data was not found to be a major handicap in understanding the hydrology of this particular area. Such data could, however, be vital for understanding the effects of drainage in areas where snow forms a higher proportion of the total precipitation. In such areas considerable attention would have to be given to avoiding the instrumental icing problems encountered in this research project.

It follows from the above qualifications that any attempt to extrapolate the findings reported in this thesis to other areas must recognise that they are due in part to the particular vegetation, climate, peat type, drainage network and age of drainage system of the study area.

REFERENCES

Ahti, E. (1974) Measuring Seasonal Moisture Variation of Drained Peatlands by Using Tensiometers. In "Proc. Int. Symp. on Forest Drainage", Jyväskylä-Oulu, Finland. pp. 81-85.

Ahti, E. (1979) Energy Relationships of Soil Water on Drained Peat. Commun. Inst. For. Fenn., 94(3): 1-56.

Ahti, E. (1980) Ditch Spacing Experiments in Estimating the Effects of Peatland Drainage on Summer Runoff. In "The Influence of Man on the Hydrological Regime with Special Reference to Representative and Experimental Basins. Proc. of the Helsinki Symp.", IAHS-AISH Publ. No. 130. pp. 49-53.

Atkinson, T.C. (1978) Techniques for Measuring Subsurface Flow on Hillslopes. In "Hillslope Hydrology", edited by Kirkby, M.J., John Wiley & Sons Ltd., Chichester. pp. 73-120.

Baden, W. and Eggelsmann, R. (1968) The Hydrologic Budget of Highbogs in the Atlantic Region. In "Proc. 3rd Int. Peat Congr.", Quebec, Runge Press Ltd., Ottawa, Canada. pp. 206-211.

Bay, R. R. (1966) Evaluation of an Evapotranspirometer for Peat Bogs. Water Resour. Res., 2(3): 437-442.

Bay, R. R. (1967) Factors Influencing Soil-Moisture Relationships in Undrained Forested Bogs. In "Int. Symp. on Forest Hydrology. Proc.", edited by Sopper, W.E. and Lull, H.W., Pergamon Press, Oxford. pp. 335-343.

Bay, R.R. (1968) The Hydrology of Several Peat Deposits in Northern Minnesota, U.S.A. In "Proc. 3rd Int. Peat Congr.", Quebec, Runge Press Ltd., Ottawa, Canada. pp. 212-218.

Bay, R.R. (1969) Runoff from Small Peatland Watersheds. J. Hydrology, 9: 90-102.

Beardsell, M.F., Jarvis, P.G. and Davidson, B. (1972) A Null-Balance Diffusion Porometer Suitable for use with Leaves of Many Shapes. J. Appl. Ecology, 9: 677-690.

Betson, R.P. (1964) What is Watershed Runoff ? J. Geophys. Res., 69(8): 1541-1552.

Binns, W.O. (1979) The Hydrological Impact of Afforestation in Great Britain. In "Man's Impact on the Hydrological Cycle in the United Kingdom", edited by Hollis, G.E., Geo Abstracts Ltd., England. pp. 55-71.

Birse, E.L. (1971) Assessment of Climatic Conditions in Scotland. 3. The Bioclimatic Sub-Regions. Map and Explanatory Pamphlet. Soil Survey of Scotland, The Macaulay Inst. for Soil Res., Aberdeen.

Boelter, D.H. (1964) Water Storage Characteristics of Several Peats in situ. Soil Sci. Soc. Am. Proc., 28: 433-435.

Boelter, D.H. (1972a) Preliminary Results of Water Level Control on Small Plots in a Peat Bog. In "Proc. 4th Int. Peat Congr.", Vol. 3, Otaniemi, Finland. pp. 347-354.

*Boelter, D.H. (1972b) Water Table Drawdown Around an Open Ditch in Organic Soils. J. Hydrology, 15: 329-340.

Boelter, D.H. (1975) Methods for Analysing the Hydrological Characteristics of Organic Soils in Marsh-Ridden Areas. In "Hydrology of Marsh-Ridden Areas. Proc. of the Minsk Symp.", The Unesco Press, IAHS, Paris. pp. 161-169.

Boelter, D.H. and Verry, E.S. (1977) Peatland and Water in the Northern Lake States. USDA For. Serv., Gen. Tech. Rep. NC-31, North Central For. Exp. Stn., Minnesota.

Boggie, R. and Miller, H.G. (1976) Growth of Pinus contorta at Different Water-Table Levels in Deep Blanket Peat. Forestry, 49: 123-131.

British Standards Institution (1965) Methods of Measurement of Liquid Flow in Open Channels. Part 4A. Thin Plate Weirs and Venturi Flumes. British Standard 3680: Part 4A, London.

Bulavko, A.G. (1971) The Hydrology of Marshes and Marsh-Ridden Lands. Nature and Resour., 7(1): 12-15.

Bulavko, A.G. and Drozd, V.V. (1975) Bog Reclamation and its Effect on the Water Balance of River Basins. In "Hydrology of Marsh-Ridden Areas. Proc. of the Minsk Symp.", The Unesco Press, IAHS, Paris. pp.461-467.

Burke, W. (1968) Drainage of Blanket Peat at Glenamoy. In "Trans. 2nd Int. Peat Congr., Leningrad", Vol. II, edited by Robertson, R.A., D.A.F.S., Edinburgh. pp. 809-817.

Burke, W. (1975a) Aspects of the Hydrology of Blanket Peat in Ireland. In "Hydrology of Marsh-Ridden Areas. Proc. of the Minsk Symp.", The Unesco Press, IAHS, Paris. pp. 171-182.

*Burke, W. (1975b) Effect of Drainage on the Hydrology of Blanket Bog. Ir. J. Agric. Res., 14: 145-162.

Calder, I.R. (1976) The Measurement of Water Losses from a Forested Area Using a "Natural" Lysimeter. J. Hydrology, 30: 311-325.

Callede, J., Hallaire, M. and Daudet, F.A. (1978) Oscillations Journalières de la Profondeur des Nappes en L'absence de Précipitations. Ann. Agron., 29(2): 111-122.

Chapin, N. (1974) New Format for Flowcharts. Software Practice and Experience, 4: 341-357.

Chapman, S.B. (1965) The Ecology of Coom Rigg Moss, Northumberland. III. Some Water Relations of the Bog System. J. Ecology, 53: 371-384.

Childs, E.C. (1969) An Introduction to the Physical Basis of Soil Water Phenomena. John Wiley & Sons Ltd., London.

Childs, E.C. (1972) Drainage Applications. In "Peat Hydrology", Inst. of Hydrology Rept. No. 16, Wallingford, U.K. pp. 9-14.

Chorley, R.J. (1978) The Hillslope Hydrological Cycle. In "Hillslope Hydrology", edited by Kirkby, M.J., John Wiley & Sons Ltd., Chichester. pp. 1-42.

Conway, V.M. and Millar, A. (1960) The Hydrology of Some Small Peat-Covered Catchments in the Northern Pennines. J. Inst. Water Engrs., 14: 415-424.

Cuttle, S.P. (1979) A Sampling Device for Proportioning Small Water Flows in Field Experiments. Lab. Practice, 28(8): 841-842.

Department of Agriculture and Fisheries for Scotland (1964) Scottish Peat Surveys. Vol. 1. South West Scotland. HMSO, Edinburgh.

Department of Agriculture and Fisheries for Scotland (1965) Scottish Peat Surveys. Vol. 3. Central Scotland. HMSO, Edinburgh.

Donald, M.G. (1973) Introduction to Hydrology. In "Handbook on the Principles of Hydrology", Section I, edited by Donald, M.G., Water Information Center, Inc., Huntington, pp.1-4.

Donald, M.G., Donald, I.N. and Wigham, J.M. (1973) Infiltration and the Physics of Flow of Water through Porous Media. In "Handbook on the Principles of Hydrology", Section V, edited by Donald, M.G., Water Information Center, Inc., Huntington. pp. 1-58.

Donald, M.G., Gordon, A.M. and Wigham, J.M. (1973) Energy, Evaporation and Evapotranspiration. In "Handbook on the Principles of Hydrology", Section III, edited by Donald, M.G., Water Information Center, Inc., Huntington. pp. 1-66.

Dooge, J. (1975) The Water Balance of Bogs and Fens. In "Hydrology of Marsh-Ridden Areas. Proc. of the Minsk Symp.", The Unesco Press, IAHS, Paris. pp. 233-271.

Douglas, J.R. (1974) Conceptual Modelling in Hydrology. Inst. of Hydrology Rept. No. 24, Wallingford, Berks.

Dunne, T. (1978) Field Studies of Hillslope Flow Processes. In "Hillslope Hydrology", edited by Kirkby, M.J., John Wiley & Sons Ltd., Chichester. pp. 227-293.

Dunne, T. and Black, R.D. (1970a) An Experimental Investigation of Runoff Production in Permeable Soils. Water Resour. Res., 6(2): 478-490.

Dunne, T. and Black, R.D. (1970b) Partial Area Contributions to Storm Runoff in a small New England Watershed. Water Resourc. Res., 6(5): 1296-1311.

Egglesmann, R. (1975) The Water Balance of Lowland Areas in North-Western Regions of the FRG. In "Hydrology of Marsh-Ridden Areas. Proc. of the Minsk Symp.", The Unesco Press, IAHS, Paris. pp. 355-367.

Fairley, R.I. (1978) Pollen Analysis as Applied to the Post-Glacial Vegetation History of a Bog at Leadburn in the Borders Region, Scotland. Unpublished Honours Thesis, University of Edinburgh.

Fleming, G. (1975) Computer Simulation Techniques in Hydrology. Elsevier, Environmental Sciences Series, New York.

Forder, H.G. (1927) The Foundations of Euclidean Geometry. Cambridge Univ. Press, Cambridge.

Forsgate, J.A., Hosegood, P.H. and McCulloch, J.S.G. (1965) Design and Installation of Semi-Enclosed Hydraulic Lysimeters. Agric. Met., 2: 43-52.

Fourcade, H.G. (1942) Some Notes on the Effects of the Incidence of Rain on the Distribution of Rainfall over the Surface of Unlevel Ground. Trans. R. Soc. S. Afr., 29: 235-254.

Gilman, K. (1971) A Semi-Quantitative Study of the Flow of Natural Pipes in Nant Gerig Sub-Catchment. Sub-surface Hydrology, Rept. No. 36, Inst. of Hydrology, Wallingford.

Gimingham, C.H. (1972) Ecology of Heathlands. Chapman and Hall, London.

Glover, J. and Forsgate, J.A. (1962) Measurement of Evapo-Transpiration from Large Tanks of Soil. Nature, 195: 1330.

Goode, D.A., Marsan, A.A. and Michaud, J.-R. (1977) Water Resources. In "Muskeg and the Northern Environment in Canada", edited by Radforth, N.W. and Brawner, C.O., Univ. Toronto Press, Toronto. pp. 229-331.

Green, M.J. (1970) Effects of Exposure on the Catch of Rain Gauges. J. Hydrology (N.Z.), 9(2): 55-71.

Heikurainen, L. (1963) On Using Ground Water Table Fluctuations for Measuring Evapotranspiration. Acta Forest. Fenn., 76-5: 1-16.

Heikurainen, L. (1968) Results of Draining Peatland for Forestry in Finland. In "Trans. 2nd Int. Peat Congr., Leningrad", Vol. II, edited by Robertson, R.A., D.A.F.S., Edinburgh. pp. 773-780.

Heikurainen, L. (1971) Ground Water Table in Drained Peat Soils and its Measurement. Acta Forest. Fenn., 113: 1-23.

Heikurainen, L. (1975) Hydrological Changes Caused by Forest Drainage. In "Hydrology of Marsh-Ridden Areas. Proc. of the Minsk Symp.", The Unesco Press, IAHS, Paris. pp.493-499.

Heikurainen, L. (1980) Effect of Forest Drainage on High Discharge. In "The Influence of Man on the Hydrological Regime with Special Reference to Representative and Experimental Basins. Proc. of the Helsinki Symp.", IAHS - AISH Publ. No. 130. pp. 89-96.

Heikurainen, L., Kenttämies, K. and Laine, J. (1978) The Environmental Effects of Forest Drainage. Suo, 29 (3-4): 49-58.

Heikurainen, L. and Laine, J. (1974) Estimating Evapotranspiration in Peatlands on the Basis of Diurnal Water Table Fluctuation. In "Proc. Int. Symp. on Forest Drainage", Jyväskylä-Oulu, Finland. pp. 87-96.

Heikurainen, L., Päivänen, J. and Sarastro, J. (1964) Ground Water Table and Water Content in Peat Soil. Acta Forest. Fenn., 77-1: 1-17.

Henman, D.W. (1963) Forest Drainage. For. Commn. Res. Branch Paper No. 26, London.

Hewlett, J.D. and Hibbert, A.R. (1967) Factors Affecting the Response of Small Watersheds to Precipitation in Humid Areas. In "Int. Symp. on Forest Hydrology. Proc.", edited by Sopper, W.E. and Lull, H.W., Pergamon Press, Oxford. pp. 275-290.

Horton, R.E. (1933) The Rôle of Infiltration in the Hydrological Cycle. Trans. Am. Geophys. Union, 14: 446-460.

Horton, R.E. (1945) Erosional Development of Streams and their Drainage Basins; Hydrophysical Approach to Quantitative Morphology. Bull. Geol. Soc. Am., 56: 275-370.

Howe, G.M., Slaymaker, H.O. and Harding, D.M. (1966) Flood Hazard in Mid-Wales. Nature, 212: 584-585.

Huff, D.D., Luxmoore, R.J., Mankin, J.B. and Begovich, C.L. (1977) TEHM: A Terrestrial Ecosystem Hydrology Model. Environmental Sciences Division, Publ. No. 1019, Oak Ridge Nat. Laboratory, Tennesse, U.S.A.

Ingram, H.A.P., Rycroft, D.W. and Williams, D.J.A. (1974) Anomalous Transmission of Water Through Certain Peats. J. Hydrology, 22: 213-218.

Ivitskii, A.I. (1968a) Evaporation from Bogs. Depending on Climate, Drainage and Cultivation. Translated from Russian by the Israel Program for Scientific Translations, available from U.S.Dept. of Commerce.

Ivitskii, A.I. (1968b) Evaporation from Peat Soil in Relation to Climatic Factors and Water Table. Translated from Russian by the Israel Program for Scientific Translations, available from the U.S.Dept. of Commerce.

Jarvis, P.G. and Stewart, J. (1979) Evaporation of Water from Plantation Forest. In "The Ecology of Even-Aged Forest Plantations. Proc. of the Meeting of Division 1", edited by Ford, E.D., Malcolm, D.C. and Atterson, J., Inst. of Terrestrial Ecology, Cambridge. pp. 327-349.

Kirkby, M.J. and Chorley, R.J. (1967) Throughflow, Overland Flow and Erosion. Bull. Int. Assoc. Sci. Hydrology, 12: 5-21.

Klueva, K.A. (1975) The Effect of Land Reclamation by Drainage on the Regime of Rivers in Byelorussia. In "Hydrology of Marsh-Ridden Areas. Proc. of the Minsk Symp.", The Unesco Press, IAHS, Paris. pp. 419-437.

Kubyshkin, G.P. (1975) Effect of Drainage Reclamation on River Flow. In "Hydrology of Marsh-Ridden Areas. Proc. of the Minsk Symp.", Gen. Discussion, The Unesco Press, IAHS, Paris. pp. 537-539.

Kuntze, H. (1974) Effects of Drainage. In "The Co-ordinators' Papers and Discussions of the Int. Symp. on Forest Drainage", Jyväskylä-Oulu, Finland. pp. 111-119.

Leavesley, G.H. (1973) A Mountain Watershed Simulation Model. Unpublished Ph.D. Thesis. Colorado State University.

Ledger, D.C. and Thom, A.S. (1977) 200 Years of Potential Moisture Deficit in South-East Scotland. Weather, 32: 342-349.

Lee, R. (1980) Forest Hydrology. Columbia Univ. Press, New York.

Lundin, K.P. (1975) Moisture Accumulation in Drained Peatlands. In "Hydrology of Marsh-Ridden Areas. Proc. of the Minsk Symp.", The Unesco Press, IAHS, Paris. pp. 85-96.

Malcolm, D.C. (1981) Silvicultural Problems of Peatlands. Paper presented to : Meeting of Div. 1, IUFRO, Thessaloniki. (in press).

McDonald, A. (1973) Some views on the Effects of Peat Drainage. Scottish Forestry, 27(4): 315-327.

Ministry of Agriculture, Fisheries and Food (1967) Potential Transpiration. Technical Bull. No. 16, London.

Moklyak, V.I., Kubyshkin, G.P. and Karkutsiev, G.N. (1975) The Effect of Drainage Works on Streamflow. In "Hydrology of Marsh-Ridden Areas. Proc. of the Minsk Symp.", The Unesco Press, IAHS, Paris. pp. 439-446.

Monteith, J.L. (1973) Principles of Environmental Physics. Edward Arnold Ltd., London.

Mosley, M.P. (1979) Streamflow Generation in a Forested Watershed, New Zealand. Water Resour. Res., 15(4): 795-806.

Mustonen, S.E. and Seuna, P. (1975) Influence of Forest Drainage on the Hydrology of an Open Bog in Finland. In "Hydrology of Marsh-Ridden Areas. Proc. of the Minsk Symp.", The Unesco Press, IAHS, Paris. pp.519-530.

Nash, J.E. and Sutcliffe, J.V. (1970) River Flow Forecasting Through Conceptual Models. Part 1. A Discussion of Principles. J. Hydrology, 10: 282-290.

Neuman, S.P. and Dasberg, S. (1977) Peat Hydrology in the Hula Basin, Israel: II. Subsurface Flow Regime. J. Hydrology, 32: 241-256.

Nichols, D.S. and Brown, J.M. (1980) Evaporation from a Sphagnum Moss Surface. J. Hydrology, 48: 289-302.

Oke, T.R. (1978) Boundary Layer Climates. John Wiley & Sons Ltd., London.

Penman, H.L. (1956) Evaporation: An Introductory Survey. Neth. J. Agric. Sci., 4:: 9-29.

Penman, H.L. (1963) Vegetation and Hydrology. Commonwealth Agric. Bur., Technical communication No. 53, Bucks, England.

Pilgrim, D.H., Huff, D.D. and Steele, T.D. (1978) A Field Evaluation of Subsurface and Surface Runoff. II. Runoff Processes. J. Hydrology, 38: 319-341.

Pitman, W.V. (1978) Flow Generation by Catchment Models of Different Complexity - A Comparison of Performance. J. Hydrology, 38: 59-70.

Reeve, R.C. and Jensen, M.C. (1949) Piezometers for Ground Water Flow Studies and Measurement of Subsoil Permeability. Agr. Eng.,30: 435-438.

Rijtema, P.E. (1965) Analysis of Actual Evapotranspiration. Agric. Res. Rept. No. 659, Centre for Agric. Publ. and Documentation, Wageningen, Netherlands.

Robertson, R.A., Nicholson, I.A. and Hughes, R. (1968) Runoff Studies on a Peat Catchment. In "Trans. 2nd Int. Peat Congr., Leningrad", Vol. I, edited by Robertson, R.A., D.A.F.S., Edinburgh. pp. 161-166.

Rodda, J.C. (1967) The Rainfall Measurement Problem. Int. Assoc. Sci. Hydrol. Publ. No. 78, IASH, Gentbrugge. pp. 215-231.

Rodda, J.C., Downing, R.A. and Law, F.M. (1976) Systematic Hydrology. Newnes - Butterworths, London.

Romanov, V.V. (1968a) Evaporation from Bogs in the European Territory of the U.S.S.R. Translated from Russian by the Israel Program for Scientific Translations, Jerusalem, H.A.Humphrey, London.

Romanov, V.V. (1968b) Hydrophysics of Bogs. Translated from Russian by the Israel Program for Scientific Translations, Jerusalem, H.A.Humphrey, London.

Rose, C.W. (1966) Agricultural Physics. Pergamon Press, Oxford.

Rycroft, D.W., Williams, D.J.A. and Ingram, H.A.P. (1975a) The Transmission of Water Through Peat. I. Review. J. Ecology, 63: 535-556.

Rycroft, D.W., Williams, D.J.A. and Ingram, H.A.P. (1975b) The Transmission of Water Through Peat. II. Field Experiments. J. Ecology, 63: 557-568.

Schulz, E.F. (1973) Problems in Applied Hydrology. Water Resour. Publ., Fort Collins, Colorado.

Seuna, P. (1974) Influence of Forest Draining on the Hydrology of an Open Bog in Finland. In "Proc. Int. Symp. on Forest Drainage", Jyväskylä-Oulu, Finland. pp. 385-393.

Seuna, P. (1980) Long-Term Influence of Forestry Drainage on the Hydrology of an Open Bog in Finland. In "The Influence of Man on the Hydrological Regime with Special Reference to Representative and Experimental Basins. Proc. of the Helsinki Symp.", IAHS-AISH Publ. No. 130. pp.141-149.

Stanhill, G. (1961) A Comparison of Methods of Calculating Potential Evapotranspiration from Climatic Data. Israel J. Agric. Res., 11(3-4): 159-171.

Starr, M.R. and Päivänen, J. (1981) The Influence of Peatland Forest Drainage on Runoff Peak Flows. Paper to be presented to : 17th IUFRO World Congr., Kyoto, Japan, Sep. 6-17, Working Parties S1.05.01 and S1.03.02.

Sturges, D.L. (1968a) Evapotranspiration at a Wyoming Mountain Bog. J. Soil Wat. Conserv., 23(1): 23-25.

Sturges, D.L. (1968b) Hydrologic Properties of Peat from a Wyoming Mountain Bog. Soil Sci., 106: 262-264.

Sutcliffe, J.V. (1972) Hydrological Studies of Peat Sites. In "Peat Hydrology", Inst. of Hydrology Rept. No. 16, Wallingford, U.K. pp. 15-20.

Thompson, D.A. (1978) Forest Ploughs. For. Commn. Leafl. 70, HMSO, Edinburgh.

Thompson, D.A. (1979) Forest Drainage Schemes. For. Commn. Leafl. 72, HMSO, Surrey.

Toebes, C. and Ouryvaev, V. (1970) Representative and Experimental Basins. An International Guide for Research and Practice. Unesco, The Netherlands.

Verma, S.B. and Cermak, J.E. (1974) Wind-Tunnel Investigation of Mass Transfer from Soil Corrugations. J. Appl. Met., 13: 578-587.

Virta, J. (1966) Measurement of Evapotranspiration and Computation of Water Budget in Treeless Peatlands in the Natural State. Commentat. Phys. - Math., Soc. Sci. Fenn., 32(11): 1-70.

Vompersky, S.E. (1974) Investigation of the Water Balance of Drained Forests and Swamps. In "Proc. Int. Symp. on Forest Drainage", Jyväskylä-Oulu, Finland. pp. 405-416.

Vorob'ev, P.K. (1963) Investigations of water yield of Low Lying Swamps of Western Siberia. Soviet Hydrology: Selected Papers,3: 226-252.

Ward, R.C. (1975) Principles of Hydrology. McGraw-Hill Book Co. Ltd., 2nd Edition, London.

Watson, A., Miller, G.R. and Green, F.H.W. (1966) Winter Browning of Heather (Calluna vulgaris)and other Moorland Plants. Trans. and Proc. of the Bot. Soc. of Edinburgh, 40(2): 195-203.

Weyman, D.R. (1970) Throughflow on Hillslopes and its Relation to the Stream Hydrograph. Bull. Int. Assoc. Sci. Hydrology, 15(2): 25-33.

Weyman, D.R. (1973) Measurement of the Downslope Flow of Water in a Soil. J. Hydrology, 20: 267-288.

Whipkey, R.Z. (1965) Subsurface Stormflow from Forested Slopes. Bull. Int. Assoc. Sci. Hydrology, 10(3): 74-85.

White, W.N. (1932) A Method of Estimating Ground-Water Supplies Based on Discharge by Plants and Evaporation from Soil. Results of Investigations in Escalante Valley, Utah. USGS Wat. Sup. Paper 659-A.

Winter, E.J. (1962) Low-Cost Weighable Lysimeters. Nature, 196: 1341-1342.

Winter, E.J. (1963) A New Type of Lysimeter. J. Hort. Sci., 38: 160-168.

World Meteorological Organization (1971) Measurement and Estimation of Evaporation and Evapotranspiration. Technical Note No. 83, WMO-No. 201, TP.105, 1966, reprinted in 1971, Geneva, Switzerland.

World Meteorological Organization (1974) Guide to Hydrological Practices. 3rd Edition, WMO-No. 168, Geneva, Switzerland.

Yesilkaya, Y. (1979) The Interception of Rainfall by Forest Canopies in South East Scotland. Unpublished Ph.D.Thesis, University of Edinburgh.

Zubets, V.M. and Murashko, M.G. (1975) Transformation of the Hydrological Regime of Marsh-Ridden Areas in the Temperate Zone by Modern Reclamation Techniques and the Prediction of their Hydrometeorological Effect. In "Hydrology of Marsh-Ridden Areas. Proc. of the Minsk Symp.", The Unesco Press, IAHS, Paris. pp. 377-385.

APPENDICES

Appendix 1:

Lysimeter installation.

To obtain an undisturbed soil-vegetation sample for the lysimeters, a special corer was screwed to the bottom of the inner cylinder (Figure 45). The corer was made of a steel pipe section with the same internal diameter and the same wall thickness as the inner cylinder, the bottom edge of the steel pipe being sharpened to give a well defined cutting edge. A shallow ring of pvc pipe was held against the steel pipe by a collar made of galvanized iron sheet screwed to both these components. The galvanized iron collar of the corer was carefully screwed to the inner cylinder, without bottom, so that the screws did not completely perforate its walls. The whole system was then carefully hammered into the peat, in a place where a good vegetation sample was available. When the inner cylinder-corer system was being pushed into the peat, the soil surface inside the inner cylinder was always level with the outside ground surface which means that little compression was experienced by the soil sample during this operation. The pvc ring of the corer prevented damage to the bottom edge of the inner cylinder. Once the inner cylinder had been pushed into the ground, so that the ground surface in the inside was just below its rim, the soil around was excavated, and the inner cylinder containing the soil-vegetation sample removed. The corer was then unscrewed from the inner cylinder, the layer of coarse sand was put in position and the bottom pvc sheet of the inner cylinder was glued to the inner cylinder walls using pvc cement and screwed with tap screws. This

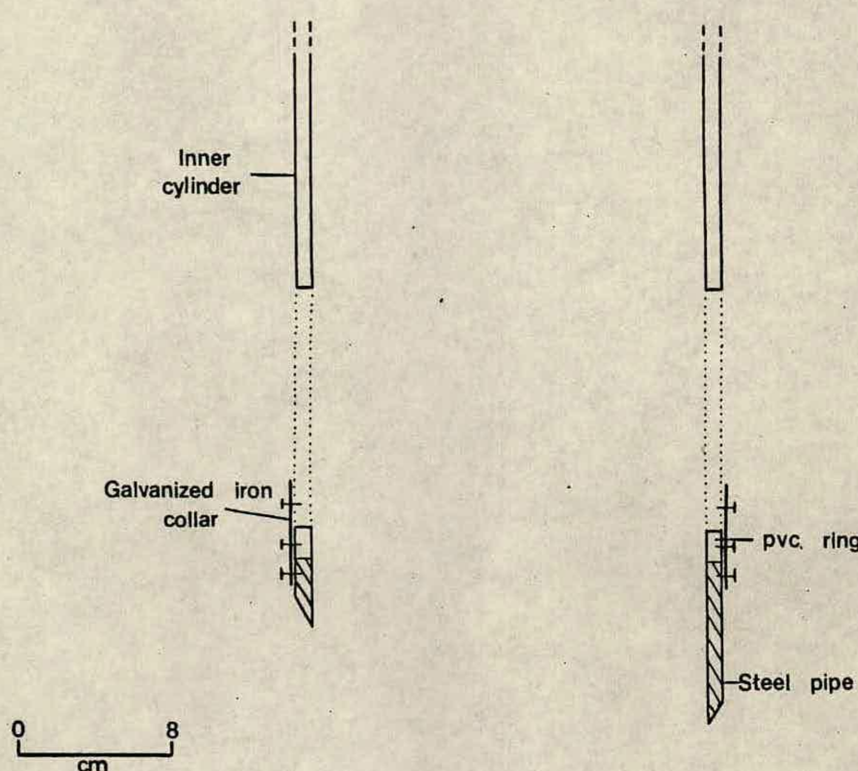


Figure 45 : Cross section of the corer used to obtain the soil-vegetation sample for the lysimeters.

bottom joint was further protected with rubber silicone sealant. The pvc cement and the rubber sealant were allowed to dry with the inner cylinder in an upside-down position to keep the glued surface free of moisture. Excavations were then made to install the outer case cylinder and the drainage system. During excavations care was taken not to disturb the surrounding area. Some difficulties were found in keeping a good vegetation sample inside so small a soil container.

Appendix 2 :

Weekly data on rainfall, runoff and water table depth under the centre of strips between 60 cm ditches for the entire period of record.

PERIOD	No. DAYS	RAINFALL (mm) RAINGAUGE No. 1	2	3	5	6	Mean	RUNOFF (mm)	WATER TABLE DEPTH (cm) At the first day of the period WELL No. 1	2	3	Mean
160377 210377	6	—	35.3	35.5	—	—	35.4	25.08	—	—	—	—
220377 280377	7	—	17.0	17.7	—	—	17.4	21.03	—	—	—	—
290377 40477	7	—	15.0	15.0	—	—	15.0	8.33	—	—	—	—
50477 110477	7	5.3	5.5	5.9	—	—	5.6	1.16	—	—	—	—
120477 180477	7	6.9	6.5	6.9	—	—	6.7	0.70	—	—	—	—
190477 250477	7	28.5	26.8	27.8	—	—	27.7	7.51	—	—	—	—
260477 20577	7	44.7	44.0	45.6	—	—	44.6	14.20	—	—	—	—
30577 90577	7	24.7	23.0	23.8	—	—	23.8	20.37	—	—	—	—
100577 160577	7	14.8	15.0	15.1	—	—	15.0	8.98	—	—	—	—
170577 230577	7	0.4	0.4	0.5	0.4	0.3	0.4	0.04	—	—	—	—
240577 300577	7	0.3	0.3	0.4	0.4	0.3	0.3	0.00	—	—	—	—
310577 60677	7	35.2	37.4	37.5	38.1	37.4	37.1	5.39	—	—	—	—
70677 130677	7	61.5	65.5	66.8	68.3	65.5	65.5	48.73	—	—	—	—
140677 200677	7	7.6	7.8	7.8	8.0	8.4	7.9	9.42	—	—	—	—
210677 270677	7	0.4	0.3	0.4	0.4	0.4	0.4	0.01	—	—	—	—
280677 40777	7	4.5	4.1	4.5	3.7	4.1	4.2	0.00	—	—	—	—
50777 110777	7	0.0	0.0	0.0	0.1	0.1	0.0	0.00	—	—	—	—
120777 180777	7	11.5	10.8	11.4	10.5	10.5	11.0	0.00	—	—	—	—
190777 250777	7	6.4	5.8	6.2	5.7	5.9	6.0	0.00	—	—	—	—
260777 10877	7	0.0	0.0	0.0	0.0	0.0	0.0	0.00	—	—	—	—
20877 80877	7	25.3	24.0	24.3	23.2	23.8	24.1	1.31	—	—	—	—
90877 150877	7	0.2	0.2	0.2	0.2	0.2	0.2	0.00	—	—	—	—
160877 220877	7	7.4	8.2	8.7	8.6	8.4	8.3	0.00	—	—	—	—
230877 290877	7	52.6	53.5	53.9	54.4	52.8	53.4	4.61	—	—	—	—
300877 50977	7	23.0	22.3	22.7	21.2	21.7	22.2	14.82	—	—	—	—
60977 120977	7	30.8	28.0	28.4	27.5	28.0	28.0	22.48	—	—	—	—
130977 190977	7	0.2	0.3	0.2	0.3	0.3	0.3	2.98	—	—	—	—
200977 260977	7	9.1	8.6	8.8	8.4	8.7	8.7	1.38	—	—	—	—
270977 31077	7	72.0	66.2	67.6	65.2	66.8	67.6	57.48	—	—	—	—
41077 101077	7	27.4	28.6	29.0	29.2	28.7	28.6	35.22	—	—	—	—
111077 171077	7	1.9	1.8	1.8	1.7	1.8	1.8	4.24	—	—	—	—

PERIOD		No. DAYS	RAINFALL(mm) RAINGAUGE No. 1	2	3	5	6	Mean	RUNOFF (mm)	WATER TABLE DEPTH (cm) At the first day of the period WELL No. 1	2	3	Mean
181077	241077	7	7.1	6.5	6.6	6.1	6.2	6.5	2.09	—	—	—	—
251077	311077	7	33.3	30.7	31.5	30.0	31.1	31.1	14.89	—	—	—	—
11177	71177	7	44.4	39.6	40.4	38.4	41.0	40.7	37.08	—	—	—	—
81177	141177	7	29.2	27.2	28.5	26.8	26.9	27.7	28.28	—	—	—	—
151177	211177	7	13.5	13.7	14.6	14.4	14.7	14.2	12.03	—	—	—	—
221177	51277	14	—	—	—	—	—	8.4	8.57	—	—	—	—
61277	121277	7	38.5	37.0	37.4	36.6	37.0	28.9	27.08	—	—	—	—
131277	191277	7	6.4	6.1	6.2	6.1	6.1	6.2	9.28	—	—	—	—
201277	261277	7	22.5	20.5	20.7	19.7	20.6	20.8	15.15	—	—	—	—
271277	20178	7	15.3	14.8	15.6	14.6	15.3	15.1	5.64	—	—	—	—
30178	230178	21	38.0	35.9	33.9	28.7	29.2	33.1	50.45	—	—	—	—
240178	60278	14	61.8	58.4	63.7	63.8	66.0	62.7	65.42	—	—	—	—
70278	270278	21	32.6	32.4	36.4	37.0	36.4	35.0	42.35	—	—	—	—
280278	60378	7	5.5	5.2	5.0	4.9	5.2	5.2	10.56	—	—	—	—
70378	130378	7	13.7	12.6	13.5	11.9	12.9	12.9	4.42	—	—	—	—
140378	200378	7	20.4	19.7	20.1	18.9	19.5	19.7	9.68	—	—	—	—
210378	270378	7	34.2	31.6	31.4	30.3	31.4	31.8	18.70	22.5	34.0	22.5	26.3
280378	30478	7	27.3	25.1	24.8	23.4	25.3	25.2	27.14	14.0	16.0	17.5	15.8
40478	90478	6	2.8	3.5	3.4	2.7	3.1	3.1	0.79	27.0	34.0	29.5	30.2
100478	170478	8	7.4	8.2	9.3	8.0	8.3	8.2	2.53	35.0	42.0	36.5	37.8
180478	240478	7	0.6	0.5	0.6	1.9	2.3	1.2	0.03	38.0	46.0	40.5	41.5
250478	10578	7	30.5	31.8	32.2	31.5	30.8	31.4	12.44	43.0	49.5	44.5	45.7
20578	80578	7	8.3	8.5	8.7	9.0	8.9	8.7	2.21	25.5	37.5	25.5	29.5
90578	150578	7	5.2	5.2	5.4	5.1	5.1	5.2	0.25	34.0	43.5	34.0	37.2
160578	220578	7	7.3	6.8	7.0	6.9	7.4	7.1	0.00	40.5	47.0	41.5	43.0
230578	290578	7	3.1	3.6	4.0	3.5	3.6	3.6	0.19	45.0	50.5	45.0	46.8
300578	50678	7	2.5	2.5	2.8	2.7	2.5	2.6	0.00	50.0	53.0	46.0	49.7
60678	120678	7	1.8	1.4	1.7	1.5	1.8	1.6	0.00	54.0	57.0	49.0	53.3
130678	190678	7	0.2	0.2	0.3	0.2	0.2	0.2	0.00	—	—	—	—
200678	260678	7	61.6	62.4	63.0	62.4	61.3	62.1	18.39	—	—	—	—
270678	30778	7	32.5	32.3	33.3	32.8	31.8	32.5	6.17	27.0	29.5	29.5	28.7

PERIOD	No. DAYS	RAINFALL (mm) RAINGAUGE No. 1	2	3	5	6	Mean	RUNOFF (mm)	WATER TABLE DEPTH (cm) (At the first day of the period) WELL No. 1	2	3	Mean
40778 100778	7	11.0	11.3	11.6	11.6	11.1	11.3	17.71	8.0	6.5	14.0	9.5
110778 170778	7	0.0	0.0	0.0	0.0	0.0	0.0	0.00	39.0	46.0	39.5	41.5
180778 240778	7	12.1	11.7	12.2	11.6	11.7	11.9	0.00	49.0	53.0	60.0	54.0
250778 310778	7	9.8	9.7	9.8	9.2	9.6	9.6	0.01	52.0	55.5	49.0	52.2
10878 70878	7	18.7	18.8	19.3	19.0	19.0	19.0	0.94	55.0	58.0	60.0	57.7
80878 140878	7	24.0	23.6	28.8	23.8	23.5	24.7	3.13	51.5	55.5	60.0	55.7
150878 210878	7	31.0	29.4	30.1	29.0	29.2	29.7	8.26	35.0	50.0	40.5	41.8
220878 280878	7	0.9	0.9	0.9	0.9	0.8	0.9	0.56	16.0	27.0	20.0	21.0
290878 40978	7	30.9	30.8	31.1	31.0	31.7	31.1	7.14	41.5	48.0	45.0	44.8
50978 110978	7	43.8	39.4	40.6	38.6	41.7	40.8	26.66	25.5	39.0	28.0	30.8
120978 190978	8	31.6	27.5	28.5	27.6	31.5	29.3	27.97	—	—	—	—
200978 250978	6	20.4	18.6	19.5	18.5	19.5	19.3	1.80	33.0	40.0	35.0	36.0
260978 21078	7	41.2	39.4	39.9	39.3	40.6	40.1	34.47	31.5	41.0	27.0	33.2
31078 91078	7	10.3	9.6	9.4	9.1	10.3	9.7	5.67	22.5	28.0	22.0	24.2
101078 161078	7	4.0	4.0	4.0	3.9	3.9	4.0	1.60	31.5	42.0	31.5	35.0
171078 231078	7	4.8	4.3	4.4	4.1	4.9	4.5	0.31	35.5	44.5	38.5	39.5
241078 301078	7	7.7	7.7	7.6	8.7	9.4	8.2	1.35	41.0	48.0	43.0	44.0
311078 61178	7	15.4	14.2	14.1	12.5	13.4	13.9	4.18	41.0	49.0	44.0	44.7
71178 131178	7	38.7	35.8	36.5	34.1	38.3	36.7	14.18	33.0	46.0	33.5	37.5
141178 201178	7	57.8	52.5	53.9	50.4	57.2	54.4	65.24	10.5	7.0	11.0	9.5
211178 271178	7	—	—	—	—	—	11.0	10.20	15.5	16.5	17.0	16.3
281178 41278	7	21.1	20.1	20.0	20.7	21.2	9.1	6.14	28.0	35.0	29.0	30.7
51278 111278	7	38.0	37.9	34.8	37.5	39.4	37.5	50.75	24.0	37.5	22.0	27.8
121278 181278	7	11.0	10.9	11.1	11.1	11.4	11.1	9.87	19.0	26.5	23.0	22.8
191278 251278	7	31.5	32.7	32.2	33.3	32.4	32.4	27.09	28.0	38.5	33.0	33.2
261278 70179	13	43.9	46.0	46.9	45.9	41.9	44.9	44.65	—	—	—	—
80179 150179	8	18.6	16.4	15.9	18.1	18.5	17.5	23.97	—	—	—	—
160179 220179	7	16.6	20.9	18.1	20.2	17.8	18.7	7.72	8.0	7.0	11.0	8.7
230179 290179	7	4.6	4.3	4.7	4.7	4.6	4.6	0.63	—	—	—	—
300179 50279	7	5.2	4.4	4.7	4.8	4.5	4.7	7.18	—	—	—	—
60279 120279	7	0.0	0.0	0.0	0.0	0.0	0.0	0.00	27.5	37.0	30.0	31.5

PERIOD		No. DAYS	RAINFALL (mm) RAINGAUGE No. 1	2	3	5	6	Mean	RUNOFF (mm)	WATER TABLE DEPTH (cm) (At the first day of the period) WELL No. 1	2	3	Mean
130279	190279	7	11.5	10.4	13.9	11.4	15.7	12.6	0.00	39.0	44.0	37.5	40.2
200279	260279	7	5.3	5.0	5.2	5.1	5.7	5.3	22.37	42.0	48.0	41.0	43.7
270279	50379	7	20.7	16.6	18.9	17.8	20.4	18.9	32.42	10.0	7.0	13.0	10.0
60379	120379	7	35.6	30.8	31.8	31.4	35.5	33.0	29.55	22.0	29.0	23.5	24.8
130379	190379	7	21.0	15.3	23.1	18.7	24.0	20.4	5.05	14.0	15.5	17.5	15.7
200379	260379	7	—	—	—	—	—	44.8	32.33	32.0	40.0	35.0	35.7
270379	20479	7	58.3	75.7	78.6	69.3	68.0	25.2	104.84	—	—	—	—
30479	90479	7	32.8	33.9	34.9	35.0	34.0	34.1	29.08	23.5	30.5	28.0	27.3
100479	160479	7	10.2	10.0	10.0	9.8	10.1	10.0	20.22	9.5	13.5	13.5	12.2
170479	230479	7	21.5	20.5	21.3	20.3	21.8	21.1	6.95	30.5	38.5	34.0	34.3
240479	300479	7	5.0	4.9	5.1	4.7	4.8	4.9	2.43	18.5	37.0	18.5	24.7
10579	60579	6	5.7	5.9	6.1	5.9	5.8	5.9	0.01	37.0	44.5	38.0	39.8
70579	150579	9	7.4	7.5	7.9	7.3	7.8	7.6	0.01	40.0	49.0	43.0	44.0
160579	220579	7	15.9	16.3	16.4	15.9	16.0	16.1	0.09	—	—	—	—
230579	280579	6	11.4	10.9	11.4	11.1	11.4	11.2	0.00	44.0	53.5	47.0	48.2
290579	40679	7	11.0	11.2	11.3	11.4	11.0	11.2	0.16	46.0	60.0	60.0	55.3
50679	110679	7	2.8	3.0	3.0	2.7	2.8	2.9	0.00	49.0	55.5	60.0	54.8
120679	180679	7	12.2	12.8	13.0	11.9	12.5	12.5	0.02	53.0	58.5	60.0	57.2
190679	250679	7	6.8	6.9	6.8	6.6	6.9	6.8	0.00	53.0	59.5	60.0	57.5
260679	20779	7	0.7	0.6	0.6	0.6	1.0	0.7	0.00	57.0	60.0	60.0	59.0
30779	90779	7	4.3	4.0	4.0	3.7	4.4	4.1	0.00	—	—	—	—
100779	160779	7	10.2	9.8	10.1	10.0	10.6	10.1	0.00	—	—	—	—
170779	230779	7	5.4	4.9	4.9	4.6	5.3	5.0	0.00	—	—	—	—
240779	300779	7	13.2	13.3	13.3	12.6	14.0	13.3	0.00	—	—	—	—
310779	60879	7	14.4	14.1	14.0	14.1	15.4	14.4	0.00	—	—	—	—
70879	130879	7	29.7	29.6	29.5	28.7	29.3	29.4	0.67	—	—	—	—
140879	200879	7	42.2	41.6	42.4	42.2	43.6	42.5	17.48	58.0	60.0	60.0	59.3
210879	270879	7	4.9	4.9	5.0	4.5	4.7	4.8	1.29	30.0	44.0	33.5	35.8
280879	30979	7	13.8	13.5	13.7	13.5	14.1	13.7	1.56	43.0	55.0	49.5	49.2
40979	100979	7	8.1	8.0	8.0	7.7	8.3	8.0	0.20	41.0	66.0	51.0	52.7
110979	170979	7	22.0	19.9	21.4	19.5	21.8	20.9	2.42	48.0	56.0	53.0	52.3

PERIOD		No. DAYS	RAINFALL(mm) RAINGAUGE No. 1	2	3	5	6	Mean	RUNOFF (mm)	WATER TABLE DEPTH(cm) At the first day of the period WELL No. 1	2	3	Mean
180979	240979	7	16.0	15.0	15.4	14.8	16.7	15.6	0.87	51.0	56.0	57.0	54.7
250979	11079	7	1.3	1.3	1.3	1.2	1.6	1.3	0.98	44.0	56.0	52.0	50.7
21079	81079	7	13.3	13.4	13.6	13.6	13.9	13.6	1.25	48.0	56.0	53.5	52.5
91079	151079	7	47.5	47.9	48.0	48.2	48.1	47.9	32.49	41.5	53.0	50.5	48.3
161079	221079	7	8.7	8.2	8.4	8.0	9.2	8.5	14.57	20.5	19.0	20.0	19.8
231079	291079	7	16.1	15.6	15.7	15.8	16.5	15.9	7.96	34.0	45.0	37.0	38.7
301079	51179	7	34.3	31.8	32.7	31.1	34.6	32.9	29.50	23.5	40.0	22.0	28.5
61179	121179	7	23.5	22.2	22.4	25.1	21.5	22.9	19.79	16.0	15.0	19.0	16.7
131179	191179	7	34.5	33.9	34.6	33.9	39.2	35.2	58.58	24.0	32.0	60.0	38.7
201179	261179	7	35.6	32.5	33.5	31.5	36.5	33.9	43.61	22.0	26.0	25.0	24.3
271179	31279	7	27.4	25.3	26.2	24.5	27.8	26.2	29.19	16.5	18.0	18.5	17.7
41279	91279	6	54.5	52.7	52.8	51.8	56.4	53.6	63.78	14.0	13.0	17.5	14.8
101279	161279	7	18.5	16.3	16.9	16.1	18.5	17.3	21.75	10.0	9.0	13.0	10.7
171279	211279	5	0.5	0.4	0.4	0.4	0.4	0.4	11.85	9.0	6.0	12.5	9.2
221279	20180	12	34.6	33.3	33.4	33.0	35.2	33.9	28.88	31.0	37.0	33.0	33.7
30180	70180	5	19.8	19.6	19.6	19.6	20.8	19.9	27.42	34.0	39.5	36.0	36.5
80180	140180	7	6.5	6.3	6.4	6.2	6.3	6.3	9.37	19.0	19.0	23.0	20.3
150180	210180	7	18.1	19.3	18.7	19.8	19.2	19.0	5.68	27.5	41.5	31.5	33.5
220180	280180	7	10.0	8.8	8.8	9.5	10.5	9.5	12.96	10.0	8.5	13.0	10.5
290180	40280	7	25.3	21.2	21.6	22.7	23.3	22.8	24.22	20.5	32.5	22.0	25.0
50280	110280	7	23.0	30.4	27.1	25.1	27.7	26.7	41.77	31.0	35.0	33.0	33.0
120280	180280	7	3.4	3.1	3.2	3.2	3.5	3.3	20.60	10.0	8.0	15.0	11.0
190280	250280	7	5.1	4.8	5.0	4.9	5.3	5.0	7.06	32.0	38.0	35.0	35.0
260280	30380	7	1.3	1.4	1.4	1.4	1.5	1.4	1.60	36.0	44.0	38.5	39.5
40380	100380	7	12.5	12.5	12.4	12.5	12.7	12.5	5.91	40.0	47.0	42.5	43.2
110380	170380	7	26.4	25.7	26.3	26.6	28.0	26.6	4.24	32.0	45.5	35.5	37.7
180380	240380	7	27.7	32.7	27.8	32.2	31.8	30.4	33.15	23.5	41.5	20.5	28.5
250380	310380	7	21.8	22.0	21.9	22.4	22.1	22.0	58.14	7.0	6.5	10.0	7.8
10480	70480	7	0.0	0.0	0.0	0.0	0.0	0.0	3.73	25.0	31.5	28.0	28.2
80480	140480	7	4.6	4.7	4.8	4.8	4.8	4.7	0.27	39.5	44.5	39.5	41.2
150480	210480	7	2.3	2.3	2.3	2.4	2.6	2.4	0.46	41.5	49.5	45.0	45.3

PERIOD		No. DAYS	RAINFALL (mm) RAINGAUGE No. 1	2	3	5	6	Mean	RUNOFF (mm)	WATER TABLE DEPTH (cm) (At the first day of the period) WELL No. 1	2	3	Mean
220480	280480	7	3.0	3.1	3.1	3.1	3.0	3.1	0.05	49.0	52.5	49.0	50.2
290480	50580	7	0.4	0.4	0.5	0.4	0.4	0.4	0.00	51.0	56.0	53.0	53.3
60580	120580	7	6.5	6.7	6.8	6.6	6.4	6.6	0.00	54.0	59.5	57.0	56.8
130580	190580	7	1.8	1.9	2.0	1.8	1.9	1.9	0.00	56.0	60.0	60.0	58.7
200580	260580	7	1.3	1.3	1.3	1.3	1.4	1.3	0.00	—	—	—	—
270580	20680	7	15.7	16.0	16.3	16.0	15.5	16.0	0.00	—	—	—	—
30680	90680	7	35.6	34.1	34.1	34.5	35.9	34.8	1.08	—	—	—	—
100680	160680	7	21.9	22.5	22.7	22.7	22.2	22.4	6.10	53.0	60.5	59.5	57.7
170680	230680	7	27.0	27.0	27.1	26.1	27.8	27.0	5.59	36.5	47.5	42.0	42.0
240680	300680	7	19.7	20.3	20.5	20.1	19.7	20.0	3.03	19.5	26.0	23.5	23.0
10780	70780	7	16.6	16.5	16.7	16.7	17.0	16.7	3.02	25.5	42.0	26.0	31.2
80780	140780	7	4.6	4.9	4.8	4.6	4.9	4.8	0.32	30.5	47.5	32.0	36.7
150780	210780	7	18.8	18.7	18.8	18.8	19.4	18.9	1.65	44.5	52.5	48.5	48.5
220780	280780	7	6.1	6.1	6.2	6.2	6.3	6.2	0.04	38.5	51.5	43.0	44.3
290780	40880	7	45.2	44.6	44.1	43.7	46.1	44.7	11.85	49.0	55.0	53.5	52.5
50880	110880	7	30.4	31.0	31.0	30.9	30.6	30.8	28.38	14.0	13.0	19.0	15.3
120880	180880	7	21.2	21.2	21.5	21.4	21.7	21.4	17.54	23.5	35.5	24.0	27.7
190880	250880	7	12.2	12.2	11.7	10.0	11.6	11.5	4.17	32.5	38.5	35.0	35.3
260880	10980	7	35.1	35.5	35.5	35.9	36.2	35.6	15.38	—	—	—	—
20980	80980	7	10.6	10.0	10.0	10.3	10.3	10.2	2.65	—	—	—	—
90980	150980	7	30.0	29.1	29.1	27.0	29.7	29.0	8.03	—	—	—	—
160980	220980	7	11.8	11.5	11.7	11.7	11.9	11.7	7.35	19.5	34.5	22.5	25.5
230980	290980	7	7.5	7.4	7.2	7.3	7.9	7.5	1.54	31.5	42.0	34.0	35.8
300980	61080	7	28.4	28.3	27.9	24.8	28.5	27.6	5.46	39.0	46.5	41.5	42.3
71080	131080	7	1.4	1.3	1.2	1.2	1.4	1.3	5.06	17.0	31.0	18.0	22.0
141080	201080	7	46.7	47.5	47.7	47.5	47.4	47.4	36.92	35.0	43.5	38.0	38.8
211080	271080	7	38.1	38.1	38.0	37.0	38.5	37.9	45.64	20.0	29.0	20.0	23.0
281080	31180	7	1.9	1.7	1.6	1.6	1.9	1.7	6.31	24.0	32.0	25.0	27.0
41180	101180	7	22.1	22.8	22.9	22.2	23.2	22.6	10.66	36.0	44.5	38.0	39.5
111180	171180	7	32.4	31.8	31.4	29.9	32.2	31.5	22.93	23.0	30.5	25.5	26.3
181180	241180	7	63.5	63.7	62.6	62.6	65.5	63.6	37.65	—	—	—	—

Appendix 3:

Detailed data on flow components for several flood events recorded at the runoff plots.

Period	Rainfall (mm)	Total Flow (litres)			Flow From Strips (litres) (covered plot) (2)	Actual Ditch Flow (litres) (1) - (2)	Impermeable Ditch Flow (litres) (Rainfall x3)
		Uncovered Plot 1	Uncovered Plot 2	Mean (1)			
14/8/79	9.5	29.60	-	29.60	0.0	29.60	28.50
15/8 - 16/8/79	6.0	13.45	-	13.45	0.0	13.45	18.00
16/8 - 18/8/79	23.5	94.15	-	94.15	0.0	94.15	70.50
10/10/79	8.5	21.52	-	21.52	0.0	21.52	25.50
11/10/79	4.5	13.45	-	13.45	0.0	13.45	13.50
13/10 - 15/10/79	34.0	188.30	-	188.30	118.80	69.50	102.00
17/10 - 18/10/79	3.5	29.59	-	29.59	24.30	5.29	10.50
19/10 - 23/10/79	5.0	48.42	-	48.42	32.40	16.02	15.00
24/10 - 26/10/79	5.5	29.59	-	29.59	13.50	16.09	16.50
28/10 - 29/10/79	7.5	34.97	-	34.97	10.80	24.17	22.50
30/10/79	3.5	21.52	-	21.52	8.10	13.40	10.50
31/10 - 2/11/79	8.0	56.49	-	56.49	32.40	24.09	24.00
2/11 - 4/11/79	16.0	129.12	-	129.12	86.40	42.72	48.00
5/11 - 6/11/79	4.0	43.04	-	43.04	24.30	18.74	12.00
17/11 - 18/11/79	12.5	207.13	-	207.13	164.70	42.40	37.50
25/11 - 26/11/79	25.0	190.99	-	190.99	113.40	77.59	75.00
14/6/80	14.0	18.87	21.28	20.07	0.0	20.07	42.00
22/6/80	8.5	10.78	10.64	10.71	0.0	10.71	25.50
23/6/80	10.0	24.26	23.94	24.10	0.0	24.10	30.00
30/6 - 1/7/80	12.5	24.26	18.62	21.44	0.0	21.44	37.50
3/7 - 4/7/80	9.5	16.18	18.62	17.39	0.0	17.39	28.50
7/7/80	7.0	13.48	7.98	10.73	0.0	10.73	21.00
17/7 - 18/7/80	12.0	8.10	5.32	6.71	0.0	6.71	36.00
19/7 - 20/7/80	7.0	13.48	13.30	13.39	0.0	13.39	21.00
4/8 - 5/8/80	22.5	94.36	85.12	89.74	18.83	70.91	67.50
7/8 - 8/8/80	20.5	121.32	151.62	136.47	69.94	66.53	61.50
11/8/80	7.0	29.26	26.60	27.93	8.07	19.86	21.00

Period	Rainfall (mm)	Total Flow (litres)			Flow From Strips (litres) (covered plot) (2)	Actual Ditch Flow (litres) (1) - (2)	Impermeable Ditch Flow (litres) (Rainfallx3)
		Uncovered Plot 1	Uncovered Plot 2	Mean (1)			
14/8 - 16/8/80	20.5	119.70	140.98	130.34	70.10	60.24	61.50
19/8 - 20/8/80	12.0	37.24	34.58	35.91	8.10	27.81	36.00
29/8/80	12.5	23.94	18.62	21.28	0.0	21.28	37.50
30/8 - 31/8/80	20.0	119.70	135.66	127.68	59.30	68.38	60.00
11/9 - 12/9/80	9.0	34.58	31.92	33.25	8.10	25.15	27.00
13/9 - 14/9/80	7.5	31.92	29.26	30.59	10.78	19.81	22.50
18/9/80	7.0	23.94	26.60	25.27	5.39	19.88	21.00
26/9 - 27/9/80	6.0	18.62	13.30	15.96	5.30	10.66	18.00
3/10 - 4/10/80	7.0	15.96	13.30	14.63	0.0	14.63	21.00
16/10 - 17/10/80	29.5	218.12	-	218.12	143.10	75.02	88.50
22/10 - 23/10/80	18.0	143.64	175.56	159.60	108.65	50.95	54.00
24/10/80	10.5	98.40	-	98.40	60.95	37.45	31.50
27/10/80	3.0	21.28	-	21.28	15.90	5.38	9.00
5/11 - 6/11/80	8.5	29.26	29.70	29.48	7.95	21.53	25.50
7/11 - 8/11/80	10.5	61.18	-	61.18	18.55	42.63	31.50
14/11/80	16.0	85.12	91.80	88.46	42.40	46.06	48.00
16/11/80	6.0	37.24	43.20	40.22	21.20	19.02	18.00
17/11/80	5.5	34.58	40.50	37.54	23.85	13.69	16.50
20/11/80	8.0	77.14	91.80	84.47	63.60	20.87	24.00
21/11/80	4.0	42.56	56.70	49.63	34.45	15.18	12.00
24/11/80	5.5	26.60	29.70	28.15	13.25	14.90	16.50
25/11/80	34.0	231.42	288.90	260.16	190.80	69.36	102.00

Appendix 4:

Weekly estimates of flow from ditches and flow from strips together with total flow and areal rainfall for the entire period of record.

PERIOD		No. DAYS	RAINFALL (mm)	FLOW(mm) TOTAL	from STRIPS	from DITCHES
160377	210377	6	35.4	25.08	20.66	35.40
220377	280377	7	17.4	21.03	22.58	17.40
290377	40477	7	15.0	8.33	5.46	15.00
50477	110477	7	5.6	1.16	0.00	3.88
120477	180477	7	6.7	0.70	0.00	2.34
190477	250477	7	27.7	7.51	0.00	25.04
260477	20577	7	44.6	14.20	1.18	44.60
30577	90577	7	23.8	20.37	18.90	23.80
100577	160577	7	15.0	8.98	6.40	15.00
170577	230577	7	0.4	0.04	0.00	0.12
240577	300577	7	0.3	0.00	0.00	0.00
310577	60677	7	37.1	5.39	0.00	17.98
70677	130677	7	65.5	48.73	41.54	65.50
140677	200677	7	7.9	9.42	10.07	7.90
210677	270677	7	0.4	0.01	0.00	0.04
280677	40777	7	4.2	0.00	0.00	0.00
50777	110777	7	0.0	0.00	0.00	0.00
120777	180777	7	11.0	0.00	0.00	0.00
190777	250777	7	6.0	0.00	0.00	0.00
260777	10877	7	0.0	0.00	0.00	0.00
20877	80877	7	24.1	1.31	0.00	4.38
90877	150877	7	0.2	0.00	0.00	0.00
160877	220877	7	8.3	0.00	0.00	0.00
230877	290877	7	53.4	4.61	0.00	15.36
300877	50977	7	22.2	14.82	11.66	22.20
60977	120977	7	28.0	22.48	20.12	28.00
130977	190977	7	0.3	2.98	4.12	0.30
200977	260977	7	8.7	1.38	0.00	4.61
270977	31077	7	67.6	57.48	53.15	67.60
41077	101077	7	28.6	35.22	38.05	28.60
111077	171077	7	1.8	4.24	5.28	1.80
181077	241077	7	6.5	2.09	0.20	6.50
251077	311077	7	31.1	14.89	7.95	31.10
11177	71177	7	40.7	37.08	35.52	40.70
81177	141177	7	27.7	28.28	28.53	27.70
151177	211177	7	14.2	12.03	11.10	14.20
221177	51277	14	8.4	8.57	8.65	8.40
61277	121277	7	28.9	27.08	26.30	28.90
131277	191277	7	6.2	9.28	10.60	6.20
201277	261277	7	20.8	15.15	12.73	20.80
271277	20178	7	15.1	5.64	1.58	15.10
30178	230178	21	33.1	50.45	57.88	33.10
240178	60278	14	62.7	65.42	66.59	62.70
70278	270278	21	35.0	42.35	45.50	35.00
280278	60378	7	5.2	10.56	12.85	5.20
70378	130378	7	12.9	4.42	0.78	12.90
140378	200378	7	19.7	9.68	5.39	19.70
210378	270378	7	31.8	18.70	13.08	31.80
280378	30478	7	25.2	27.14	27.98	25.20
40478	90478	6	3.1	0.79	0.00	2.63

PERIOD		No. DAYS	RAINFALL (mm)	FLOW(mm) TOTAL	from STRIPS	from DITCHES
100478	170478	8	8.2	2.53	0.10	8.20
180478	240478	7	1.2	0.03	0.00	0.09
250478	10578	7	31.4	12.44	4.31	31.40
20578	80578	7	8.7	2.21	0.00	7.37
90578	150578	7	5.2	0.25	0.00	0.84
160578	220578	7	7.1	0.00	0.00	0.02
230578	290578	7	3.6	0.19	0.00	0.63
300578	50678	7	2.6	0.00	0.00	0.00
60678	120678	7	1.6	0.00	0.00	0.00
130678	190678	7	0.2	0.00	0.00	0.00
200678	260678	7	62.1	18.39	0.00	61.31
270678	30778	7	32.5	6.17	0.00	20.57
40778	100778	7	11.3	17.71	20.46	11.30
110778	170778	7	0.0	0.00	0.00	0.00
180778	240778	7	11.9	0.00	0.00	0.00
250778	310778	7	9.6	0.01	0.00	0.03
10878	70878	7	19.0	0.94	0.00	3.12
80878	140878	7	24.7	3.13	0.00	10.43
150878	210878	7	29.7	8.26	0.00	27.54
220878	280878	7	0.9	0.56	0.41	0.90
290878	40978	7	31.1	7.14	0.00	23.79
50978	110978	7	40.8	26.66	20.60	40.80
120978	190978	8	29.3	27.97	27.39	29.30
200978	250978	6	19.3	1.80	0.00	6.01
260978	21078	7	40.1	34.47	32.06	40.10
31078	91078	7	9.7	5.67	3.94	9.70
101078	161078	7	4.0	1.60	0.58	4.00
171078	231078	7	4.5	0.31	0.00	1.03
241078	301078	7	8.2	1.35	0.00	4.49
311078	61178	7	13.9	4.18	0.01	13.90
71178	131178	7	36.7	14.18	4.52	36.70
141178	201178	7	54.4	65.24	69.89	54.40
211178	271178	7	11.0	10.20	9.86	11.00
281178	41278	7	9.1	6.14	4.87	9.10
51278	111278	7	37.5	50.75	56.43	37.50
121278	181278	7	11.1	9.87	9.34	11.10
191278	251278	7	32.4	27.09	24.81	32.40
261278	70179	13	44.9	44.65	44.54	44.90
80179	150179	8	17.5	23.97	26.74	17.50
160179	220179	7	18.7	7.72	3.01	18.70
230179	290179	7	4.6	0.63	0.00	2.10
300179	50279	7	4.7	7.18	8.24	4.70
60279	120279	7	0.0	0.00	0.00	0.00
130279	190279	7	12.6	0.00	0.00	0.00
200279	260279	7	5.3	22.37	29.68	5.30
270279	50379	7	18.9	32.42	38.22	18.90
60379	120379	7	33.0	29.55	28.07	33.00
130379	190379	7	20.4	5.05	0.00	16.82
200379	260379	7	44.8	32.33	26.99	44.80
270379	20479	7	25.2	104.84	138.97	25.20

PERIOD		No DAYS	RAINFALL (mm)	FLOW(mm) TOTAL	from STRIPS	from DITCHES
30479	90479	7	34.1	29.08	26.92	34.10
100479	160479	7	10.0	20.22	24.60	10.00
170479	230479	7	21.1	6.95	0.89	21.10
240479	300479	7	4.9	2.43	1.37	4.90
10579	60579	6	5.9	0.01	0.00	0.04
70579	150579	9	7.6	0.01	0.00	0.04
160579	220579	7	16.1	0.09	0.00	0.29
230579	280579	6	11.2	0.00	0.00	0.00
290579	40679	7	11.2	0.16	0.00	0.54
50679	110679	7	2.9	0.00	0.00	0.00
120679	180679	7	12.5	0.02	0.00	0.06
190679	250679	7	6.8	0.00	0.00	0.00
260679	20779	7	0.7	0.00	0.00	0.00
30779	90779	7	4.1	0.00	0.00	0.00
100779	160779	7	10.1	0.00	0.00	0.00
170779	230779	7	5.0	0.00	0.00	0.00
240779	300779	7	13.3	0.00	0.00	0.00
310779	60879	7	14.4	0.00	0.00	0.00
70879	130879	7	29.4	0.67	0.00	2.23
140879	200879	7	42.5	17.48	6.75	42.50
210879	270879	7	4.8	1.29	0.00	4.30
280879	30979	7	13.7	1.56	0.00	5.21
40979	100979	7	8.0	0.20	0.00	0.67
110979	170979	7	20.9	2.42	0.00	8.08
180979	240979	7	15.6	0.87	0.00	2.91
250979	11079	7	1.3	0.98	0.84	1.30
21079	81079	7	13.6	1.25	0.00	4.17
91079	151079	7	47.9	32.49	25.88	47.90
161079	221079	7	8.5	14.57	17.17	8.50
231079	291079	7	15.9	7.96	4.56	15.90
301079	51179	7	32.9	29.50	28.05	32.90
61179	121179	7	22.9	19.79	18.46	22.90
131179	191179	7	35.2	58.58	68.60	35.20
201179	261179	7	33.9	43.61	47.77	33.90
271179	31279	7	26.2	29.19	30.48	26.20
41279	91279	6	53.6	63.78	68.15	53.60
101279	161279	7	17.3	21.75	23.66	17.30
171279	211279	5	0.4	11.85	16.75	0.40
221279	20180	12	33.9	28.88	26.73	33.90
30180	70180	5	19.9	27.42	30.65	19.90
80180	140180	7	6.3	9.37	10.69	6.30
150180	210180	7	19.0	5.68	0.00	18.95
220180	280180	7	9.5	12.96	14.44	9.50
290180	40280	7	22.8	24.22	24.84	22.80
50280	110280	7	26.7	41.77	48.22	26.70
120280	180280	7	3.3	20.60	28.01	3.30
190280	250280	7	5.0	7.06	7.95	5.00
260280	30380	7	1.4	1.60	1.68	1.40
40380	100380	7	12.5	5.91	3.09	12.50
110380	170380	7	26.6	4.24	0.00	14.15

PERIOD		No. DAYS	RAINFALL (mm)	FLOW (mm)		
				TOTAL	from STRIPS	from DITCHES
180380	240380	7	30.4	33.15	34.33	30.40
250380	310380	7	22.0	58.14	73.63	22.00
10480	70480	7	0.0	3.73	5.32	0.00
80480	140480	7	4.7	0.27	0.00	0.89
150480	210480	7	2.4	0.46	0.00	1.55
220480	280480	7	3.1	0.05	0.00	0.15
290480	50580	7	0.4	0.00	0.00	0.00
60580	120580	7	6.6	0.00	0.00	0.00
130580	190580	7	1.9	0.00	0.00	0.00
200580	260580	7	1.3	0.00	0.00	0.00
270580	20680	7	16.0	0.00	0.00	0.00
30680	90680	7	34.8	1.08	0.00	3.62
100680	160680	7	22.4	6.10	0.00	20.34
170680	230680	7	27.0	5.59	0.00	18.65
240680	300680	7	20.0	3.03	0.00	10.11
10780	70780	7	16.7	3.02	0.00	10.06
80780	140780	7	4.8	0.32	0.00	1.07
150780	210780	7	18.9	1.65	0.00	5.50
220780	280780	7	6.2	0.04	0.00	0.13
290780	40880	7	44.7	11.85	0.00	39.49
50880	110880	7	30.8	28.38	27.34	30.80
120880	180880	7	21.4	17.54	15.89	21.40
190880	250880	7	11.5	4.17	1.03	11.50
260880	10980	7	35.6	15.38	6.72	35.60
20980	80980	7	10.2	2.65	0.00	8.83
90980	150980	7	29.0	8.03	0.00	26.76
160980	220980	7	11.7	7.35	5.49	11.70
230980	290980	7	7.5	1.54	0.00	5.14
300980	61080	7	27.6	5.46	0.00	18.20
71080	131080	7	1.3	5.06	6.67	1.30
141080	201080	7	47.4	36.92	32.42	47.40
211080	271080	7	37.9	45.64	48.96	37.90
281080	31180	7	1.7	6.31	8.28	1.70
41180	101180	7	22.6	10.66	5.54	22.60
111180	171180	7	31.5	22.93	19.25	31.50
181180	241180	7	63.6	37.65	26.52	63.60

Appendix 5:

Weekly evapotranspiration estimates yielded by the lysimeters during the 1980 growing season.

Period	No. Days	Actual evapotranspiration (mm)			
		Lysimeter No.			
		2	3*	4	5*
29/4 - 5/5/80	7	7.2	17.9	16.5	13.5
6/5 - 12/5/80	7	6.5	14.5	14.5	7.3
13/5 - 19/5/80	7	17.1	24.5	25.3	23.5
20/5 - 26/5/80	7	12.5	17.4	15.2	15.2
27/5 - 2/6/80	7	10.5	8.8	11.7	6.6
3/6 - 9/6/80	7	12.3	13.4	17.3	15.6
10/6 - 16/6/80	7	14.5	13.3	13.0	10.9
17/6 - 23/6/80	7	14.0	13.9	16.9	11.9
24/6 - 30/6/80	7	14.7	20.9	18.5	16.6
1/7 - 4/7/80	3	4.9	5.2	5.2	5.0
4/7 - 7/7/80	4	10.4	7.7	8.8	8:4
8/7 - 14/7/80	7	17.9	24.0	20.4	20.2
15/7 - 21/7/80	7	13.9	10.0	13.0	10.0
22/7 - 28/7/80	7	15.1	18.4	16.9	12.1
29/7 - 4/8/80	7	8.0	7.0	7.0	4.1
5/8 - 11/8/80	7	9.8	10.8	14.2	10.0
12/8 - 18/8/80	7	12.2	19.3	18.3	12.5
19/8 - 25/8/80	7	15.4	14.4	14.4	-
26/8 - 1/9/80	7	13.4	14.5	14.6	-
2/9 - 8/9/80	7	12.3	-	16.6	-
9/9 - 15/9/80	7	5.1	-	7.2	-
16/9 - 22/9/80	7	9.8	-	8.5	-
23/9 - 29/9/80	7	12.0	-	16.1	-
30/9 - 6/10/80	7	13.8	-	20.0	-
7/10 - 13/10/80	7	6.6	-	4.5	-
14/10 - 20/10/80	7	1.0	-	2.3	-
21/10 - 27/10/80	7	0.0	-	0.0	-
28/10 - 3/11/80	7	9.2	-	10.0	-

* Lysimeters with taller vegetation. Data corrected for windy and rainy periods.

Appendix 6:

Weekly data on total flow, groundwater flow and interflow recorded from the runoff plots during the 1980 growing season.

Period	Flow from strips (covered plot) (litres)		Total Flow (uncovered plots) (litres)	
	Groundwater flow (40-60 cm deep layer + bottom ditch)	Interflow (20-40 cm deep layer)	Plot 1	Plot 2
29/4 - 5/5/80	0.0	0.0	0.0	0.0
6/5 - 12/5/80	0.0	0.0	0.0	0.0
13/5 - 19/5/80	0.0	0.0	0.0	0.0
20/5 - 26/5/80	0.0	0.0	0.0	0.0
27/5 - 2/6/80	0.0	0.0	0.0	0.0
3/6 - 9/6/80	0.0	0.0	0.0	0.0
10/6 - 16/6/80	0.0	2.65	18.87	21.28
17/6 - 23/6/80	0.0	0.0	35.05	34.58
24/6 - 30/6/80	0.0	0.0	21.57	15.96
1/7 - 7/7/80	0.0	0.0	35.05	31.92
8/7 - 14/7/80	0.0	0.0	2.70	0.0
15/7 - 21/7/80	0.0	0.0	21.57	18.62
22/7 - 28/7/80	0.0	0.0	0.0	0.0
29/7 - 4/8/80	5.38	0.0	88.97	77.14
5/8 - 11/8/80	121.05	18.55	204.14	242.06
12/8 - 18/8/80	88.77	2.65	146.30	178.22
19/8 - 25/8/80	16.14	0.0	50.54	42.56
26/8 - 1/9/80	56.49	7.95	146.30	162.26
2/9 - 8/9/80	18.83	2.65	47.88	42.56
9/9 - 15/9/80	26.90	0.0	103.74	95.76
16/9 - 22/9/80	53.44	0.0	87.78	98.42
23/9 - 29/9/80	15.90	0.0	34.58	31.92
30/9/80	2.65	0.0	2.66	0.0

Appendix 7:

Computer program for the model written in a form of Fortran designed for the Edinburgh Regional Computer Centre.

```
      DIMENSION R(12),QO(12),K1(50),QOB(12,50),
     1SI(12,50),SG(12,50),QI(12,50),QG(12,50),QS(14,52),
     2QT(12,50),QT2(50),QOB2(50),R1(12),DSB(12,50),
     3RE(50),I1(50),I2(50),I3(50)
C
C     INITIALIZATION OF ARRAYS AND VARIABLES
C
      SUM=0.000
      SUMO=0.000
      F=0.000
      FO=0.000
      SUMO2=0.000
      SUM2=0.000
      F2=0.000
      FO2=0.000
      DO 6 IROW=1,52
      DO 7 ICOL=1,14
      QS(ICOL,IROW)=0.000
    7 CONTINUE
    6 CONTINUE
C
C     READ VALUES OF MODEL PARAMETERS
C
      READ(2,200)RG,RI,SIO,SGO,Y1,Y2,Y3
      READ(5,201)ADS,AD36,AID,GMA,GMI,PEREVA,DSBO
C
C     READ VALUES OF TWO-HOURLY RAINFALL
C
      DO 1 IROW=1,50
      READ(3,202)K1(IROW),(R(ICOL),ICOL=1,12)
C
C     READ VALUES OF OBSERVED TWO-HOURLY FLOWS
C
      READ(4,203)I1(IROW),I2(IROW),I3(IROW),(QO(ICOL),ICOL=1,12)
C
C     READ DAILY POTENCIAL EVAPOTRANSPIRATION
C
      READ(7,700)K3,RE(IROW)
      QT2(IROW)=0.000
      QOB2(IROW)=0.000
      DO 2 ICOL=1,12
      IF(R(ICOL).EQ.9.9)R(ICOL)=11.2
C
C     COMPUTING GROUNDWATER FLOW,INTERFLOW AND SURFACE FLOW FROM
C     THE STRIP COMPONENT
C
      QOB(ICOL,IROW)=QO(ICOL)
      ARE=0.000
      IF(ICOL.GE.5.AND.ICOL.LE.9.AND.R(ICOL).EQ.0.0)ARE=RE(IROW)/5
      IF(ICOL.EQ.1)GO TO 40
```

```
      QG(ICOL,IROW)=RG*SG(ICOL-1,IROW)
      IF(QG(ICOL,IROW).LT.0.000)QG(ICOL,IROW)=0.000
      SG(ICOL,IROW)=SG(ICOL-1,IROW)-QG(ICOL,IROW)+R(ICOL)+
     1SI(ICOL-1,IROW)-ARE
      GO TO 43
   40 QG(ICOL,IROW)=RG*SGO
      IF(QG(ICOL,IROW).LT.0.000)QG(ICOL,IROW)=0.000
      SG(ICOL,IROW)=SGO-QG(ICOL,IROW)+R(ICOL)+SIO-ARE
   43 IF(SG(ICOL,IROW).LT.GMA)GO TO 50
      SI(ICOL,IROW)=SG(ICOL,IROW)-GMA
      SG(ICOL,IROW)=GMA
      GO TO 45
   50 SI(ICOL,IROW)=0.000
   45 R1(ICOL)=0.0
      IF(SI(ICOL,IROW).LE.GMI)GO TO 90
      R1(ICOL)=SI(ICOL,IROW)-GMI
      SI(ICOL,IROW)=GMI
   90 QI(ICOL,IROW)=RI*SI(ICOL,IROW)
      SI(ICOL,IROW)=SI(ICOL,IROW)-QI(ICOL,IROW)
C
C     COMPUTING AREA OF DITCH SLOPES WORKING AS IMPERMEABLE
C
      PERI=SG(ICOL,IROW)*ADS/GMA
      IF(PERI.LE.0.000)PERI=0.000
C
C     BALANCE FOR THE BOTTOM OF THE DITCH
C
      IF(ICOL.EQ.1)DSB(ICOL,IROW)=DSBO+ARE*PEREVA-
     1QG(ICOL,IROW)*AID/AD36
      IF(ICOL.NE.1)DSB(ICOL,IROW)=DSB(ICOL-1,IROW)+ARE*
     1PEREVA-QG(ICOL,IROW)*AID/AD36
      IF(DSB(ICOL,IROW).GT.0.000)GO TO 111
      QG(ICOL,IROW)=-DSB(ICOL,IROW)*AD36/AID
      DSB(ICOL,IROW)=0.000
      GO TO 75
  111 QG(ICOL,IROW)=0.000
      DSB(ICOL,IROW)=DSB(ICOL,IROW)-R(ICOL)
      IF(DSB(ICOL,IROW).LT.0.000)GO TO 70
      R(ICOL)=0.000
      GO TO 75
   70 R(ICOL)=-DSB(ICOL,IROW)
      DSB(ICOL,IROW)=0.000
C
C     COMPUTING SURFACE FLOW OUTPUT
C
   75 AUX=(R(ICOL)*(AD36+PERI)+R1(ICOL)*AID)/(AID+AD36+ADS)
      QS(ICOL,IROW)=QS(ICOL,IROW)+AUX*Y1
      QS(ICOL+1,IROW)=QS(ICOL+1,IROW)+AUX*Y2
      QS(ICOL+2,IROW)=QS(ICOL+2,IROW)+AUX*Y3
C
C     COMPUTING TOTAL TWO-HOURLY OUTFLOW
C
      QT(ICOL,IROW)=QS(ICOL,IROW)+(QG(ICOL,IROW)+QI(ICOL,IROW))
     1*AID/(AID+AD36+ADS)
```

```
C
C     BEGINNING OF COMPUTATION OF ERROR FUNCTION
C
      F=F+(QT(ICOL,IROW)-QOB(ICOL,IROW))**2
      SUMO=SUMO+QOB(ICOL,IROW)
      SUM=SUM+QT(ICOL,IROW)
C
C     COMPUTING TOTAL DAILY OUTFLOW
C
      QT2(IROW)=QT2(IROW)+QT(ICOL,IROW)
      QOB2(IROW)=QOB2(IROW)+QOB(ICOL,IROW)
C
C     END OF LOOP LOOKING AT EACH TWO-HOURLY TIME-STEP
C
    2 CONTINUE
      SGO=SG(12,IROW)
      SIO=SI(12,IROW)
      DSBO=DSB(12,IROW)
      QS(1,IROW+1)=QS(13,IROW)
      QS(2,IROW+1)=QS(14,IROW)
      SUMO2=SUMO2+QOB2(IROW)
      SUM2=SUM2+QT2(IROW)
      F2=F2+(QOB2(IROW)-QT2(IROW))**2
C
C     END OF LOOP LOOKING AT EACH DAY
C
    1 CONTINUE
      DO 3 IROW=1,50
      DO 4 ICOL=1,12
      FO=FO+(QOB(ICOL,IROW)-SUMO/(50*12))**2
    4 CONTINUE
      FO2=FO2+(QOB2(IROW)-SUMO2/50)**2
    3 CONTINUE
      R2=100*(FO-F)/FO
      R22=100*(FO2-F2)/FO2
      WRITE(6,500)SUM,SUMO,R2
      DO 8 IROW=1,50
      WRITE(6,501)K1(IROW),(QT(ICOL,IROW),ICOL=1,12)
      WRITE(6,502)I1(IROW),I2(IROW),I3(IROW),(QOB(ICOL,IROW),ICOL=1,12)
    8 CONTINUE
      WRITE(6,500)SUM2,SUMO2,R22
      DO 9 IROW=1,50
      WRITE(6,601)I1(IROW),I2(IROW),I3(IROW),QT2(IROW),QOB2(IROW)
    9 CONTINUE
  200 FORMAT(F5.3,1X,F4.2,1X,F3.1,1X,F6.2,3(1X,F5.3))
  201 FORMAT(3(F7.5,1X),F4.1,1X,F3.1,1X,F4.2,1X,F3.1)
  202 FORMAT(I6,12(1X,F3.1))
  203 FORMAT(1X,I2,I2,I2,12(1X,F6.4))
  500 FORMAT(F9.4,1X,F9.4,1X,F6.2)
  501 FORMAT(I7,12(1X,F6.4))
  502 FORMAT(1X,I2,I2,I2,12(1X,F6.4))
  601 FORMAT(1X,I2,I2,I2,1X,F9.4,1X,F9.4)
  700 FORMAT(I6,1X,F3.1)
      STOP
      END
```

Appendix 8:

Parameter values, input data files and output of the model for the run for the 1978 period.

1. MODEL PARAMETERS

AID = 1.757 ha

ADS = 0.591 ha

AD36 = 0.162 ha

GMA = 18.0 mm

RG = 0.02

GMI = 9.0 mm

RI = 0.2

SGO = 4.0 mm

SIO = 0.0 mm

PEREVA = 0.35

DSBO = 0.0 mm

Y1 = 0.582

Y2 = 0.347

Y3 = 0.071

2. INPUT DATA FILES

RAINFALL

(two-hourly values - mm)

041078	0.0	0.0	0.0	0.1	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.1
051078	0.2	0.0	0.0	0.1	0.0	0.4	0.6	0.4	1.1	0.0	0.0	0.0
061078	0.2	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
071078	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
081078	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
091078	0.0	0.0	0.2	0.0	3.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0
101078	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0
111078	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
121078	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
131078	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
141078	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
151078	0.0	0.0	0.0	0.4	0.0	0.0	0.3	1.3	1.4	0.0	0.0	0.0
161078	0.0	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
171078	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
181078	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
191078	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0
201078	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
211078	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.2	0.0	0.0	0.2	0.4
221078	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
231078	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3
241178	0.3	0.0	0.4	1.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
251078	0.0	0.0	0.0	0.0	0.0	0.7	2.5	1.2	0.0	0.3	0.0	0.0
261078	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
271078	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
281078	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
291078	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
301078	0.0	0.0	0.0	0.1	0.0	0.0	0.0	1.0	0.6	0.0	0.0	0.0
311078	0.0	0.0	0.0	0.0	0.0	0.3	2.5	1.6	1.2	0.0	0.0	0.0
011178	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
021178	0.0	0.0	0.0	2.3	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
031178	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	1.8	0.0	0.0	0.0
041178	0.3	0.0	0.5	0.0	0.0	0.3	0.1	0.2	0.3	2.0	0.0	0.0
051178	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
061178	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
071178	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
081178	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
091178	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
101178	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.2	0.0	0.0
111178	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
121178	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	5.6	1.7	0.7	0.5
131178	0.0	7.7	0.0	0.0	0.0	0.0	1.5	1.8	2.0	2.1	0.0	0.0
141178	0.0	0.0	2.7	3.5	2.5	2.9	0.0	1.0	0.0	0.5	0.2	0.3
151178	1.5	3.0	2.5	1.3	1.7	4.5	4.5	1.0	0.0	0.7	2.3	1.0
161178	0.4	0.8	1.8	1.2	2.3	8.5	0.5	0.3	1.2	0.2	1.1	0.0
171178	0.2	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.6	0.9	0.0
181178	0.1	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
191178	0.0	0.1	0.6	0.1	0.0	0.0	0.0	0.0	0.8	1.0	0.5	0.3
201178	0.2	0.2	0.7	0.5	0.0	0.1	0.0	0.0	0.0	2.5	2.2	0.4
211178	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3
221178	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.2	1.9	0.0	0.0

POTENTIAL EVAPOTRANSPIRATION

(Daily values - mm)

041078	1.0
051078	1.0
061078	1.0
071078	0.4
081078	0.4
091078	0.4
101078	0.4
111078	0.4
121078	0.4
131078	0.4
141078	0.5
151078	0.5
161078	0.5
171078	0.5
181078	0.5
191078	0.5
201078	0.5
211078	0.8
221078	0.8
231078	0.8
241078	0.8
251078	0.8
261078	0.8
271078	0.8
281078	0.2
291078	0.2
301078	0.2
311078	0.2
011178	0.2
021178	0.2
031178	0.2
041178	0.8
051178	0.8
061178	0.8
071178	0.8
081178	0.8
091178	0.8
101178	0.8
111178	0.7
121178	0.7
131178	0.7
141178	0.7
151178	0.7
161178	0.7
171178	0.7
181178	0.3
191178	0.3
201178	0.3
211178	0.3
221178	0.3

OBSERVED FLOWS

(two-hourly values - mm)

41078	0.0909	0.0909	0.0909	0.0788	0.0788	0.1326	0.1122	0.0581	0.0366	0.0330	0.0366	0.0485
51078	0.0626	0.0626	0.0530	0.0626	0.0485	0.0682	0.1122	0.0858	0.1965	0.1341	0.0848	0.0677
61078	0.0788	0.0732	0.0793	0.0914	0.0581	0.0403	0.0366	0.0237	0.0123	0.0086	0.0086	0.0103
71078	0.0140	0.0185	0.0209	0.0209	0.0209	0.0209	0.0209	0.0140	0.0072	0.0058	0.0058	0.0072
81078	0.0120	0.0140	0.0161	0.0185	0.0209	0.0209	0.0185	0.0161	0.0161	0.0185	0.0209	0.0209
91078	0.0209	0.0237	0.0330	0.0265	0.8521	0.3439	0.1524	0.0636	0.0269	0.0209	0.0209	0.0209
101078	0.0209	0.0209	0.0209	0.0209	0.0209	0.0209	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265
111078	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0237	0.0185	0.0103	0.0086	0.0086	0.0086
121078	0.0103	0.0120	0.0120	0.0120	0.0161	0.0209	0.0140	0.0072	0.0058	0.0058	0.0058	0.0058
131078	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0037	0.0037	0.0037
141078	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058
151078	0.0058	0.0058	0.0058	0.0209	0.0161	0.0120	0.0209	0.2011	0.2247	0.0858	0.0444	0.0330
161078	0.0265	0.0209	0.0209	0.0209	0.0444	0.0297	0.0209	0.0161	0.0103	0.0058	0.0058	0.0058
171078	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0037	0.0037	0.0029	0.0021	0.0021
181078	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
191078	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
201078	0.0010	0.0040	0.0089	0.0029	0.0016	0.0007	0.0004	0.0004	0.0001	0.0001	0.0001	0.0001
211078	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0007	0.0010	0.0021	0.0021	0.0040	0.0185
221078	0.0209	0.0297	0.0185	0.0103	0.0058	0.0048	0.0037	0.0021	0.0016	0.0010	0.0010	0.0010
231078	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
241078	0.0012	0.0029	0.0072	0.0498	0.0530	0.0407	0.0237	0.0140	0.0048	0.0016	0.0010	0.0010
251078	0.0010	0.0010	0.0010	0.0010	0.0010	0.0016	0.0881	0.2636	0.1418	0.0793	0.0793	0.0444
261078	0.0297	0.0237	0.0209	0.0161	0.0161	0.0161	0.0140	0.0120	0.0086	0.0072	0.0058	0.0058
271078	0.0058	0.0058	0.0058	0.0058	0.0058	0.0037	0.0037	0.0021	0.0016	0.0010	0.0004	0.0004
281078	0.0004	0.0004	0.0007	0.0010	0.0016	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021
291078	0.0021	0.0021	0.0021	0.0037	0.0037	0.0058	0.0058	0.0048	0.0021	0.0010	0.0010	0.0010
301078	0.0010	0.0016	0.0021	0.0037	0.0037	0.0037	0.0037	0.0762	0.0808	0.0297	0.0185	0.0120
311078	0.0103	0.0086	0.0058	0.0058	0.0058	0.0194	0.3091	0.3261	0.2066	0.1046	0.0530	0.0297
11178	0.0209	0.0185	0.0120	0.0120	0.0086	0.0086	0.0086	0.0072	0.0058	0.0058	0.0058	0.0058
21178	0.0058	0.0058	0.0483	0.4820	0.1730	0.0682	0.0407	0.0185	0.0120	0.0120	0.0120	0.0120
31178	0.0120	0.0120	0.0120	0.0164	0.0489	0.0237	0.0140	0.0992	0.1046	0.0581	0.0485	0.0485
41178	0.0485	0.0485	0.0793	0.0530	0.0581	0.0530	0.0581	0.0626	0.1825	0.1889	0.1046	0.0732
51178	0.0576	0.0530	0.0485	0.0444	0.0366	0.0330	0.0265	0.0209	0.0161	0.0161	0.0161	0.0161
61178	0.0161	0.0161	0.0161	0.0161	0.0161	0.0161	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120
71178	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086
81178	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058
91178	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021
101178	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021	0.0048	0.0072	0.0120	0.0120	0.0120
111178	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0086	0.0086	0.0086
121178	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0103	0.9789	0.4798	0.3126	0.2768
131178	0.1341	1.7990	0.8218	0.3697	0.2285	0.1683	0.4142	0.4928	0.7186	1.2850	0.6286	0.4142
141178	0.2868	0.2881	0.8784	1.4200	1.8072	1.6687	1.2924	1.0586	0.6286	0.5694	0.5322	0.4455
151178	0.4790	1.0882	1.2690	1.5281	1.2969	2.3553	3.8237	2.8171	1.6972	1.2898	1.5549	1.2601
161178	1.1109	1.0830	1.2924	1.2957	1.5226	5.2353	2.7264	1.9219	1.9361	1.1685	1.2690	0.9495
171178	0.8251	0.9495	0.8521	0.6081	0.5512	0.4965	0.4295	0.3683	0.3258	0.3829	0.5337	0.4798
181178	0.3836	0.3398	0.3683	0.3544	0.3126	0.2623	0.2278	0.2066	0.2066	0.1865	0.1865	0.1865
191178	0.1771	0.1771	0.1771	0.2391	0.1965	0.1589	0.1336	0.1182	0.1111	0.1871	0.2768	0.2510
201178	0.2072	0.2072	0.2072	0.3000	0.1965	0.1589	0.1259	0.1111	0.1040	0.7138	0.5572	0.4295
211178	0.2749	0.2278	0.2172	0.1965	0.1771	0.1589	0.1589	0.1589	0.1501	0.1501	0.1683	0.1865
221178	0.1418	0.1182	0.1040	0.0909	0.0788	0.0677	0.0677	0.0677	0.6775	0.7685	0.3265	0.2391

3. OUTPUT

The first line of the model output shows the sums of two-hourly computed and observed flows, in mm, and the "efficiency" of the model for two-hourly flows. The next 100 lines show respectively the two-hourly computed and observed flows, in mm/2h, for each day. Two lines are assigned to each day: the first of these lines shows two-hourly computed flows and the second two-hourly observed flows.

The line No.102 of the model output shows the sums of daily computed and observed flows and the "efficiency" of the model for daily flows. The last fifty lines of the output show respectively the computed and observed daily flows, in mm/day, for each day.

109.4510	95.3201	95.31										
41078	0.0560	0.0549	0.0538	0.0593	0.0525	0.0984	0.0823	0.0554	0.0456	0.0464	0.0454	0.0507
41078	0.0909	0.0909	0.0909	0.0788	0.0788	0.1326	0.1122	0.0581	0.0366	0.0330	0.0366	0.0485
51078	0.0614	0.0552	0.0475	0.0513	0.0448	0.0678	0.1018	0.1089	0.1650	0.1268	0.0817	0.0700
51078	0.0626	0.0626	0.0530	0.0626	0.0485	0.0682	0.1122	0.0858	0.1965	0.1341	0.0848	0.0677
61078	0.0837	0.0790	0.0704	0.1058	0.0914	0.0688	0.0599	0.0558	0.0518	0.0524	0.0514	0.0503
61078	0.0788	0.0732	0.0793	0.0914	0.0581	0.0403	0.0366	0.0237	0.0123	0.0086	0.0086	0.0103
71078	0.0493	0.0483	0.0474	0.0464	0.0437	0.0417	0.0397	0.0377	0.0358	0.0358	0.0350	0.0343
71078	0.0140	0.0185	0.0209	0.0209	0.0209	0.0209	0.0209	0.0140	0.0072	0.0058	0.0058	0.0072
81078	0.0336	0.0330	0.0323	0.0317	0.0292	0.0275	0.0258	0.0241	0.0225	0.0227	0.0222	0.0218
81078	0.0120	0.0140	0.0161	0.0185	0.0209	0.0209	0.0185	0.0161	0.0161	0.0185	0.0209	0.0209
91078	0.0213	0.0209	0.0305	0.0288	0.3217	0.3199	0.1594	0.0884	0.0775	0.0766	0.0751	0.0736
91078	0.0209	0.0237	0.0330	0.0265	0.8521	0.3439	0.1524	0.0636	0.0269	0.0209	0.0209	0.0209
101078	0.0721	0.0706	0.0692	0.0678	0.0647	0.0622	0.0760	0.0700	0.0608	0.0585	0.0573	0.0562
101078	0.0209	0.0209	0.0209	0.0209	0.0209	0.0209	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265
111078	0.0550	0.0539	0.0529	0.0518	0.0490	0.0468	0.0447	0.0427	0.0407	0.0405	0.0397	0.0389
111078	0.0265	0.0265	0.0265	0.0265	0.0265	0.0265	0.0237	0.0185	0.0103	0.0086	0.0086	0.0086
121078	0.0381	0.0374	0.0366	0.0359	0.0334	0.0315	0.0298	0.0280	0.0263	0.0264	0.0259	0.0254
121078	0.0103	0.0120	0.0120	0.0120	0.0161	0.0209	0.0140	0.0072	0.0058	0.0058	0.0058	0.0058
131078	0.0249	0.0244	0.0239	0.0234	0.0211	0.0195	0.0180	0.0165	0.0150	0.0153	0.0150	0.0147
131078	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0037	0.0037	0.0037
141078	0.0238	0.0225	0.0178	0.0163	0.0137	0.0120	0.0103	0.0086	0.0070	0.0077	0.0075	0.0074
141078	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058
151078	0.0072	0.0071	0.0070	0.0245	0.0206	0.0105	0.0224	0.0918	0.1654	0.1126	0.0600	0.0480
151078	0.0058	0.0058	0.0058	0.0209	0.0161	0.0120	0.0209	0.2011	0.2247	0.0858	0.0444	0.0330
161078	0.0470	0.0461	0.0452	0.0505	0.0676	0.0580	0.0458	0.0411	0.0389	0.0389	0.0381	0.0374
161078	0.0265	0.0209	0.0209	0.0209	0.0444	0.0297	0.0209	0.0161	0.0103	0.0058	0.0058	0.0058
171078	0.0366	0.0359	0.0352	0.0345	0.0315	0.0294	0.0274	0.0254	0.0235	0.0238	0.0233	0.0229
171078	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058	0.0037	0.0037	0.0029	0.0021	0.0021
181078	0.0224	0.0220	0.0215	0.0211	0.0184	0.0166	0.0148	0.0131	0.0114	0.0120	0.0117	0.0115
181078	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
191078	0.0113	0.0110	0.0108	0.0106	0.0081	0.0065	0.0049	0.0034	0.0124	0.0118	0.0077	0.0066
191078	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010
201078	0.0065	0.0336	0.0309	0.0176	0.0118	0.0101	0.0084	0.0068	0.0052	0.0059	0.0058	0.0057
201078	0.0010	0.0040	0.0089	0.0029	0.0016	0.0007	0.0004	0.0004	0.0001	0.0001	0.0001	0.0001
211078	0.0056	0.0055	0.0054	0.0053	0.0015	0.0109	0.0068	0.0124	0.0072	0.0046	0.0117	0.0287
211078	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0007	0.0010	0.0021	0.0021	0.0040	0.0185
221078	0.0323	0.0361	0.0278	0.0196	0.0139	0.0113	0.0087	0.0063	0.0038	0.0091	0.0088	0.0067
221078	0.0209	0.0297	0.0185	0.0103	0.0058	0.0048	0.0037	0.0021	0.0016	0.0010	0.0010	0.0010
231078	0.0061	0.0060	0.0058	0.0057	0.0020	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0053
231078	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
241178	0.0149	0.0102	0.0208	0.0676	0.0858	0.0516	0.0274	0.0207	0.0180	0.0189	0.0185	0.0181
241078	0.0012	0.0029	0.0072	0.0498	0.0530	0.0407	0.0237	0.0140	0.0048	0.0016	0.0010	0.0010
251078	0.0178	0.0174	0.0171	0.0167	0.0128	0.0490	0.2170	0.2582	0.1465	0.1043	0.0864	0.0740
251078	0.0010	0.0010	0.0010	0.0010	0.0010	0.0016	0.0881	0.2636	0.1418	0.0793	0.0793	0.0444
261078	0.0698	0.0684	0.0670	0.0656	0.0716	0.0652	0.0582	0.0538	0.0505	0.0508	0.0497	0.0487
261078	0.0297	0.0237	0.0209	0.0161	0.0161	0.0161	0.0140	0.0120	0.0086	0.0072	0.0058	0.0058
271078	0.0478	0.0468	0.0459	0.0450	0.0404	0.0373	0.0343	0.0313	0.0283	0.0291	0.0285	0.0279
271078	0.0058	0.0058	0.0058	0.0058	0.0058	0.0037	0.0037	0.0021	0.0016	0.0010	0.0004	0.0004
281078	0.0274	0.0268	0.0263	0.0257	0.0243	0.0233	0.0222	0.0212	0.0202	0.0201	0.0197	0.0193
281078	0.0004	0.0004	0.0007	0.0010	0.0016	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021
291078	0.0189	0.0186	0.0182	0.0178	0.0222	0.0262	0.0221	0.0183	0.0168	0.0167	0.0164	0.0161
291078	0.0021	0.0021	0.0021	0.0037	0.0037	0.0058	0.0058	0.0048	0.0021	0.0010	0.0010	0.0010
301078	0.0158	0.0154	0.0151	0.0195	0.0178	0.0147	0.0133	0.0657	0.0922	0.0616	0.0384	0.0336
301078	0.0010	0.0016	0.0021	0.0037	0.0037	0.0037	0.0037	0.0762	0.0808	0.0297	0.0185	0.0120
311078	0.0329	0.0322	0.0316	0.0310	0.0294	0.0458	0.2279	0.3164	0.3048	0.1870	0.1149	0.0991
311078	0.0103	0.0086	0.0058	0.0058	0.0058	0.0194	0.3091	0.3261	0.2066	0.1046	0.0530	0.0297
11178	0.0972	0.0952	0.0933	0.1001	0.1049	0.0959	0.0884	0.0850	0.0827	0.0814	0.0798	0.0782
11178	0.0209	0.0185	0.0120	0.0120	0.0086	0.0086	0.0086	0.0072	0.0058	0.0058	0.0058	0.0058
21178	0.0766	0.0751	0.0736	0.2871	0.4586	0.2912	0.1539	0.1230	0.1200	0.1179	0.1156	0.1132
21178	0.0058	0.0058	0.0483	0.4820	0.1730	0.0682	0.0407	0.0185	0.0120	0.0120	0.0120	0.0120
31178	0.1110	0.1088	0.1066	0.1045	0.1706	0.1499	0.1148	0.1037	0.2921	0.2385	0.1458	0.1202
31178	0.0120	0.0120	0.0120	0.0164	0.0489	0.0237	0.0140	0.0992	0.1046	0.0581	0.0485	0.0485
41178	0.1486	0.1380	0.1729	0.1529	0.1222	0.1451	0.1449	0.1457	0.1601	0.3704	0.2856	0.1692
41178	0.0485	0.0485	0.0793	0.0530	0.0581	0.0530	0.0581	0.0626	0.1825	0.1889	0.1046	0.0732

51178	0.1381	0.1353	0.1326	0.1300	0.1238	0.1190	0.1143	0.1097	0.1052	0.1044	0.1023	0.1002
51178	0.0576	0.0530	0.0485	0.0444	0.0366	0.0330	0.0265	0.0209	0.0161	0.0161	0.0161	0.0161
61178	0.0982	0.0963	0.0944	0.0925	0.0870	0.0830	0.0790	0.0751	0.0713	0.0711	0.0697	0.0683
61178	0.0161	0.0161	0.0161	0.0161	0.0161	0.0161	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120
71178	0.0670	0.0656	0.0643	0.0630	0.0582	0.0547	0.0513	0.0479	0.0447	0.0451	0.0442	0.0433
71178	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086
81178	0.0424	0.0416	0.0407	0.0520	0.0455	0.0367	0.0322	0.0293	0.0264	0.0271	0.0266	0.0261
81178	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0058	0.0058	0.0058	0.0058	0.0058	0.0058
91178	0.0255	0.0250	0.0245	0.0240	0.0199	0.0172	0.0146	0.0120	0.0094	0.0105	0.0103	0.0101
91178	0.0037	0.0037	0.0037	0.0037	0.0037	0.0037	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021
101178	0.0099	0.0097	0.0095	0.0093	0.0055	0.0031	0.0007	0.0232	0.0180	0.0177	0.0143	0.0101
101178	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021	0.0048	0.0072	0.0120	0.0120	0.0120
111178	0.0132	0.0127	0.0104	0.0185	0.0144	0.0080	0.0048	0.0026	0.0006	0.0017	0.0017	0.0016
111178	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0086	0.0086	0.0086
121178	0.0016	0.0016	0.0015	0.0015	0.0000	0.0000	0.0000	0.0146	0.4680	0.5142	0.3222	0.2213
121178	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	0.0086	-0.0103	0.9789	0.4798	0.3126	0.2768
131178	0.1539	1.3250	0.9376	0.3615	0.2070	0.2008	0.4297	0.6517	0.8633	1.1644	0.7037	0.3987
131178	0.1341	1.7990	0.8218	0.3697	0.2285	0.1683	0.4142	0.4928	0.7186	1.2850	0.6286	0.4142
141178	0.2832	0.2520	1.0235	1.8259	1.9553	2.1247	1.3592	1.1822	0.8380	0.7682	0.6427	0.5704
141178	0.2868	0.2881	0.8784	1.4200	1.8072	1.6687	1.2924	1.0586	0.6286	0.5694	0.5322	0.4455
151178	0.8966	1.5857	1.8503	1.5887	1.5535	2.4748	3.6916	2.6187	1.3653	1.0896	1.5533	1.4320
151178	0.4790	1.0882	1.2690	1.5281	1.2969	2.3553	3.8237	2.8171	1.6972	1.2898	1.5549	1.2601
161178	1.0814	1.0014	1.2971	1.2947	1.5915	4.7141	3.1670	1.5284	1.2719	1.0107	1.0680	0.7824
161178	1.1109	1.0830	1.2924	1.2957	1.5226	5.2353	2.7264	1.9219	1.9361	1.1685	1.2690	0.9495
171178	0.6173	0.8769	0.6429	0.4303	0.2993	0.2488	0.2459	0.2389	0.2682	0.3529	0.4544	0.3488
171178	0.8251	0.9495	0.8521	0.6081	0.5512	0.4965	0.4295	0.3683	0.3258	0.3829	0.5337	0.4798
181178	0.2755	0.2796	0.2893	0.2891	0.2531	0.2282	0.2188	0.2136	0.2084	0.2048	0.2007	0.1967
181178	0.3836	0.3398	0.3683	0.3544	0.3126	0.2623	0.2278	0.2066	0.2066	0.1865	0.1865	0.1865
191178	0.1927	0.2028	0.2797	0.2575	0.2061	0.1845	0.1782	0.1738	0.2786	0.3832	0.3569	0.2944
191178	0.1771	0.1771	0.1771	0.2391	0.1965	0.1589	0.1336	0.1182	0.1111	0.1871	0.2768	0.2510
201178	0.2551	0.2419	0.3119	0.3333	0.2541	0.2179	0.1994	0.1880	0.1816	0.5578	0.8016	0.5674
201178	0.2072	0.2072	0.2072	0.3000	0.1965	0.1589	0.1259	0.1111	0.1040	0.7138	0.5572	0.4295
211178	0.3716	0.2747	0.2382	0.2275	0.2216	0.2163	0.2111	0.2060	0.2010	0.1975	0.2077	0.2420
211178	0.2749	0.2278	0.2172	0.1965	0.1771	0.1589	0.1589	0.1589	0.1501	0.1501	0.1683	0.1865
221178	0.2185	0.1928	0.1838	0.1802	0.1752	0.1708	0.1665	0.1623	0.6299	0.7842	0.4615	0.2562
221178	0.1418	0.1182	0.1040	0.0909	0.0788	0.0677	0.0677	0.0677	0.6775	0.7685	0.3265	0.2391

109.4528	95.3211	97.60
41079	0.7008	0.8879
51078	0.9822	1.0386
61078	0.8208	0.5212
71078	0.4952	0.1770
81078	0.3264	0.2134
91078	1.2937	1.6057
101078	0.7855	0.2844
111078	0.5567	0.2373
121078	0.3746	0.1277
131078	0.2318	0.0633
141078	0.1546	0.0570
151078	0.5772	0.6763
161078	0.5545	0.2280
171078	0.3494	0.0551
181078	0.1964	0.0120
191078	0.1052	0.0084
201078	0.1484	0.0203
211078	0.1056	0.0290
221078	0.1843	0.1004
231078	0.0310	0.0084
241078	0.3725	0.2009
251078	1.0171	0.7031
261078	0.7192	0.1760
271078	0.4425	0.0419
281078	0.2765	0.0188
291078	0.2283	0.0352
301078	0.4030	0.2367
311078	1.4529	1.0848
11178	1.0820	0.1196
21178	2.0058	0.8903
31178	1.7664	0.4979
41178	2.1554	1.0103
51178	1.4149	0.3849
61178	0.9858	0.1686
71178	0.6492	0.1236
81178	0.4266	0.0864
91178	0.2033	0.0348
101178	0.1312	0.0627
111178	0.0902	0.1338
121178	1.5466	2.1186
131178	7.3974	7.4748
141178	12.8254	10.8759
151178	21.7001	20.4593
161178	19.8086	21.5113
171178	5.0247	6.8025
181178	2.8577	3.2215
191178	2.9884	2.2036
201178	4.1100	3.3185
211178	2.8149	2.2252
221178	3.5820	2.7484

Appendix 9: Glossary of symbols used in the model.

AD36	-Area occupied by ditch bottoms.
ADS	-Area occupied by ditch slopes.
AID	-Area occupied by strips.
ARE	-Two-hourly potential evapotranspiration.
AUX	-Total rainfall excess for the whole area.
DSB	-Deficit to saturation of ditch bottoms.
DSBO	-Initial value for deficit to saturation of ditch bottoms.
F	-Sum of the squares of differences between observed and computed two-hourly flows.
F2	-Sum of the squares of differences between observed and computed daily flows.
FO	-Sum of the squares of the deviations of the two-hourly observed flows from their mean.
FO2	-Sum of the squares of the deviations of the daily observed flows from their mean.
GMA	-Maximum value for groundwater storage.
GMI	-Maximum value for subsurface storage.
ICOL	-Two-hourly time-step number.
Kr	-Two-hourly recession constant of groundwater flow.
Kri	-Two-hourly recession constant of interflow.
PEREVA	-Ratio between the evaporation from ditch bottoms and the potential evapotranspiration.
PERI	-Area of ditch slopes working as impermeable.
QG	-Groundwater flow.
QI	-Interflow.
QOB	-Observed two-hourly flow output.
QOB2	-Observed daily flow output.
QS	-Total surface flow.
QT	-Computed two-hourly flow output.
QT2	-Computed daily flow output.
R	-Rainfall.
R1	-Surface flow from strips.
R2	-"Efficiency" for two-hourly flow predictions.
R22	-"Efficiency" for daily flow predictions.
RE	-Daily potential evapotranspiration.
RG	-Groundwater storage constant.
RI	-Subsurface storage constant.
SG	-Groundwater storage.
SGO	-Initial value for groundwater storage.
SI	-Subsurface storage.
SIO	-Initial value for subsurface storage.
SUM	-Sum of two-hourly computed flows.
SUM2	-Sum of daily computed flows.
SUMO	-Sum of two-hourly observed flows.
SUMO2	-Sum of daily observed flows.
Y1, Y2, Y3	-Proportions of the total surface flow, originated by a two-hourly unit rainfall excess, occurring respectively during the two-hourly time-steps ICOL, ICOL+1, ICOL+2.